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THE EFFECTS OF LENGTH OF GRADE

ON THE QUALITY OF TRAFFIC FLOW

A THESIS

Presented to

The Faculty of the Graduate Division

by

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In Partial Fulfillment

of the Requirements of the Degree

Master of Science in Civil Engineering

Georgia Institute of Technology

September, 1967

THE EFFECTS OF LENGTH OF GRADE

ON THE QUALITY OF TRAFFIC FLOW

Approved:

Chairman

Date approved by Chairman:

ACKNOWLEDGMENTS

The author wishes to extend his appreciation for the assistance given him by three groups of people. The first group consists of members of the faculty at Georgia Institute of Technology. Special thanks go to his thesis advisor, Dr. Paul H. Wright, for his help, guidance and suggestions throughout the preparation of this thesis. Also, appreciation is extended to Dr. Donald O. Covault and Professor Radnor J. Paquette for serving on the reading committee and for their helpful comments regarding the content and organization of this thesis.

Without the assistance of personnel from the State Highway Department of Georgia this research could not have been carried out. Special appreciation is extended to Mr. William S. Derrick, State Highway Traffic and Safety Engineer, for his assistance in obtaining equipment and permission for working on the Atlanta Interstate system. Also appreciation is extended to Mr. L. W. Verner, Aerial Surveys Laboratory, and Mr. D. B. McCoy, pilot, for their assistance in obtaining data.

The third group consists of many people. They are the author's fellow students at Georgia Institute of Technology who have given assistance in collecting data and helpful suggestions throughout the entire work on this thesis. It is to these aspiring fellow students that the author wishes to dedicate this effort.

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SUMMARY

Investigation of the effects of grade and length of grade on different sizes of trucks has shown that there is a definite decrease in truck speeds as ascending grades and lengths of grades increase. Research has also been conducted on the shape of the curves found when the following variables are plotted: speed-density, volume-density and speed-volume.

The purpose of this thesis was to study the effects that the length of grade has upon the flow of traffic on a freeway system. Two sites of equal grade (2.75 per cent), but different lengths of grade (813 and 3,400 feet), on the Northeast Expressway in Atlanta, Georgia, were chosen for study. Speeds, volumes, and densities, obtained during peak-hour and non peak-hour traffic conditions, were determined at three or four positions along the length of grade at each site, and the three curves were plotted from these data for each position. The data were obtained by time-lapse aerial photography, time-lapse movies and a 20-pen event recorder in conjunction with pneumatic tube detectors. The effect of the length of grade was determined by the change in the speed-density-volume curves.

The results showed that some of the curves changed position and shape, which indicated a variation in the level of service of the roadway. This variation of level of service may have been caused by downstream interchanges and not by lengths of grades. When level

of service F occurred on the long length of grade, the long grade contributed in the reduction of speeds.

CHAPTER I

INTRODUCTION

The major method of travelling a short distance in the United States is by automobile. One reason for the building of high-speed expressways is to provide a means of reducing total travel time. When urban areas are encountered, speeds of motor vehicles usually decrease and congestion develops during peak-hour traffic movements. High losses due to lengthened travel time occur during periods of congestion when traffic movements come to a complete, or near complete, halt.

In order to insure the best, most efficient use of the expressways the highway engineer must locate and remove the causes of congestion. Three major causes of congestion are human, such as slow driving or accidents; environmental or weather conditions; and physical, such as geometric design or interchanges. The highway engineer is directly connected with controlling the physical causes.

Purpose

The intent of this thesis is to present a method for determining the effects of length of grade upon the quality of traffic flow. The length of grade on an expressway may be a cause of congestion and may seriously impede the flow of traffic under certain conditions. In highly populated areas it is necessary to keep lengths of grade below a certain critical value in order to help maintain the movement of traffic. This is especially true during peak-hours and in an area with a high percentage of truck movements.

Three measurements of traffic flow present a description of how smoothly the traffic is moving, or that is to say, the quality of the traffic flow. These measurements are speed, volume (vehicles per unit time) and density (vehicles per unit distance). Past research (1), (2), (3), (4)* has shown that there is a relationship between these measurements and that a plot of two of the three will yield a predictable curve. In plotting curves by data taken at different test areas, the shape of the curves may remain similar, but the positions of the curves may change.

In 1961 M. Ross Palmer (5) suggested that this change in curves may occur. He said, "The q:k [volume: Density] curve would change in magnitude and possibly in shape with different weather conditions and also with changes in road cross section, clearances and sight distances, etc." A change in the position of two curves will indicate a change in the quality of traffic flow which may be caused by the differences in the two areas studied. It is the attempt of this study to determine whether or not the effects of length of grade on the quality of traffic flow can be determined by using the above mentioned method.

Literature Research

During the past several decades, a large number of studies on the effect of grade on traffic flow characteristics have been published. In his experiment in 1930 A. N. Johnson (6) defined where the point of

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*Numbers in parentheses refer to numbered references in Literature Cited at the end of this thesis.

congestion in traffic flow begins and gives a conclusion of what congestion does to the traffic.

> Congestion is considered to occur on a road when the number of vehicles reaches a total great enough to fill the road and make turning out impracticable; this condition to last a sufficient length of time to be noticeable, the minimum amount of time being one minute.
>
> When congestion occurs, reduction of speed will be noticed, along with the tendency for drivers to crowd one another. (p. 218)

In his study he found that two-lane and three-lane roadways were free flowing until volumes of 1,000 vehicles per hour and 1,600 vehicles per hour, respectively, were reached. The second value was determined when heavy flow occurred in one direction. There was insufficient traffic on four-lane highways for him to reach any conclusions.

Research in the field of congestion was continued in 1934 by B. D. Greenshields (2) who collected data by using a 16 mm movie camera operating at a rate of 88 frames per minute. Of interest in this research is that he formulated that speed and density were related linearly and, therefore, speed and volume were related parabolically.

One of the earliest studies which specifically dealt with the effect of grades on traffic flow was that made by R. E. Toms (7) in 1936. His conclusions were that heavy vehicles will slow down when they encounter long, sustained grades of 6 or 7 per cent. When horizontal curvature was encountered with the uphill grade, grades less than 6 per cent caused the traffic to lose speed. If the reduced speeds occurred over a long enough time interval, congestion began to occur. R. G. Browning (8), in 1938, said that the maximum grade should be 8 per cent, and the minimum grade should be 1/2 per cent on the major road systems.

He also stated that there was a need to put equal emphasis on sight distance encountered in vertical curves as was presently being given to horizontal curves.

A study in 1941 by O. K. Normann (9) showed that, where sight distance was sufficient to allow drivers to see an approaching hill, speeds were generally different at the bottom of the grade than on level ground. This indicated that drivers would increase their speed when aware of an approaching hill. During this same year C. C. Saal (10) presented charts which showed the loss in truck speeds for a given grade and length of grade. He stated that a 3 per cent grade should be the maximum value allowed since there was a large increase in loss of speed when going to a maximum grade of 4 per cent. If a truck had an initial speed of 35 miles per hour, its speed would not be reduced to less than 20 miles per hour on a 6 per cent, 800 feet long grade.

In 1945 A. Taragin (11) did research on the effect of length of grade for trucks of different sizes (light, medium and heavy). Most of his data came from the research by C. C. Saal previously mentioned. One of his conclusions was that if a grade was long enough, the motor vehicle would reach a constant speed on the grade which is independent of the initial speed at the beginning of the grade. He found that a heavy truck on a 3 per cent grade would drop from 30 miles per hour to 20 miles per hour if the length of grade were 900 feet.

W. E. Willey (12) in 1949 did a study on the effects of mountain grades on trucks. He observed the effects of grades from 2 per cent to 6 per cent, at elevations from sea level to 7,200 feet and under traffic volumes of 1,000 to 3,000 vehicles per day. He concluded that a 2 per cent and a 3 per cent grade would cause a loss of 2 miles per hour and 5 miles per hour per 1,000 feet length of grade, respectively. G. Webb and K. Moskowitz (13) made a study, in 1957, at the other extreme of traffic flow-urban freeway conditions. They studied the Santa Anna Freeway (a four-lane freeway) in California and found that congestion occurred at a site where the grade was only 1.7 per cent and 800 feet long. The congestion occurred even when the truck percentage was as low as 2 per cent. From this they concluded that congestion could be caused by grade alone without the influence of trucks. They also concluded that truck percentages of reasonable size could have considerable effect on traffic flow even on low percentage grades.

In 1958 J. Legarra (14) made a study concerned with the high volumes of traffic in Los Angeles. A conclusion which is relevant to this research was that when volumes approach the capacity of the street, traffic becomes very sensitive to low grades, such as 1 or 2 per cent. The most recent article found was by L. Newman and K. Moskowitz (15). In 1965 they made a study of the effects of grades and truck percentage on the service volume of a multilane highway under a given level of service. They found that 35 miles per hour appears to be a critical speed, below which congestion occurred more easily. Another conclusion, which is obvious but which has not been mentioned before this, was that if sight distance is sufficient the effect of grade may be decreased. In such a case an automobile approaching a truck on a grade would have time to make the decision to move into the inside lane and pass the truck without losing speed due to the presence of the truck.

Both the *Highway Capacity Manual* (16) and *A Policy on Geometric*

Design of Rural Highways (17) contain lengthy discussions on the subject of grades, the length of grades and their effects on traffic flow. Charts relating grade, length of grade and loss in truck speed are included. The major sources for this information contained in these books were the researchers listed above. Additional research has been made on the effects of grade and length of grade on traffic flow as related to mountainous terrain, rural roads and non-urban freeways. Since the present research is concerned only with urban freeway conditions, the above research will not be discussed but has been listed in "Other References" at the end of this report.

CHAPTER II

EQUIPMENT

Three procedures were used for the collection of field data: time-lapse aerial photography (for obtaining speeds and density), time-lapse movies (for obtaining speeds and volume), and an Esterline-Angus 20-pen event recorder used in conjunction with pneumatic tube detectors (for obtaining speeds).

Originally data was to be obtained by using time-lapse aerial photography, and Test I was made using this method. An Aero-Commander airplane with a cruising speed of 180 miles per hour was used for flying. A Wild R-8C camera, mounted in the plane, took vertical photographs on nine inch by nine inch negatives. The camera had a focal length of six inches and an automatic timer for taking the pictures. Measurements were read directly from the negatives by using a portable light board.

During Test I time-lapse movies were also taken. Two Paillard Bolex 16 mm movie cameras were used. Each was driven by a Bodine 110-volt AC synchronous motor which was geared to run the film at 100 frames per minute (0.6 seconds per frame). The power was provided by using a 12-volt heavy duty battery and a 75-watt continuous, 100-watt intermittent vibrator-type converter. A Kodak Analyst Movie Projector was used for obtaining the desired measurements from the time-lapse movies.

Test II and Test III involved the use of pneumatic tubes placed across the roadway. Attached to each tube was a diaphragm which was connected to a channel on the 20-pen event recorder. An Esterline-Angus "Operation (Event) Recorder" was used to record the data. The recorder was driven by a Bodine 110-volt AC synchronous motor. The power was provided by using a 12-volt battery and a 75-watt continuous, 100-watt intermittent vibrator-type convertor for Test II and by connecting the motor directly to 115-volt AC current for Test III.

A Burroughs B-5500 Computer was used for making all lengthy calculations. Except for the Regression Analysis Program (18), each program was written specifically for the desired computations.

CHAPTER III

STATISTICAL PROCEDURES

Sample Size

In calculating the mean speed for each period of time observed, it was necessary to determine the sample size needed to meet certain minimum requirements placed on the research. The following equation was used to determine the desired sample size.

$$N = \frac{Z^2 S^2}{d^2} \tag{1}$$

where N = the minimum sample size to be tested,

Z = the normal deviate corresponding to the desired confidence level,

S = the estimated standard deviation of the sample,

d = the permitted error in the estimate.

To obtain meaningful results, J. C. Oppenlander (19) has indicated that a minimum value for N is 30 units.

Statistical Tests

Three different tests were used to determine whether two sets of data came from the same population. First, an "F-Test" was performed to determine whether the variances of the samples were the same at a given confidence level of $(1 - \alpha)$ per cent. The following equation was used to find the observed F value.

$$F = \frac{S_1^2}{S_2^2} \tag{2}$$

where α = Type I error in statistics,

S_1^2 = Variance of the mean for set 1,

S_2^2 = Variance of the mean for set 2,

N1 = Sample size for set 1,

N2 = Sample size for set 2.

If this value of F was within $\pm F_{\alpha,(N1,N2)}$ range then the null hypothesis was accepted, otherwise it was rejected. The null hypothesis is that the variances of the two sets of data are equal.

If the "F-Test" were accepted, then the second and third tests are valid. The second test, the stronger of the last two tests when applicable, is the "T-Test." The null hypothesis is that the means of the values of the two sets of data are equal. It should be noted that as a set of data becomes less like a straight line and more complex, the third test is probably more meaningful. The observed T was found as follows:

$$T = \frac{(\bar{X}1 - \bar{X}2)}{S_d} \tag{3}$$

$$S_d = \sqrt{\left[\frac{1}{N1} + \frac{1}{N2}\right]\left[\frac{(N1-1)S_1^2 + (N2-1)S_2^2}{N1 + N2 - 2}\right]} \tag{4}$$

where $\bar{X}1$ = Mean value for set 1.

$\bar{X}2$ = Mean value for set 2.

This value is tested against $\pm T_{\alpha,(N1+N2-2)}$, and if it is within these limits then the null hypothesis, that the means of the values are equal, is accepted, otherwise it is rejected.

When comparing two sets of data of equal sample size, the paired observation test, "PO-Test," can be used. This test differs from the second test in that it tests the differences between pairs of individual values in each set of data. In this case the observed T is found by the following equation:

$$T = \frac{\bar{d}\ \sqrt{N}}{S_d} \tag{5}$$

where $\bar{d}$ = the mean of the differences,

S_d = the variance of the differences,

and tested against $\pm T_{\alpha,(N-1)}$. The null hypothesis is accepted if the observed T is within the above range, otherwise it is rejected.

Regression Analysis

After obtaining the values or speed, density and volume, plots were made of these values to obtain a best fit curve (line) for the observed values. Regression analysis (20) was used to calculate the best fit curve. "A General Multiple Regression and Correlation Analysis Program" (18) used for this research established the best fit curve by the method of least squares. This method gives all observed values equal weight and finds the curve such that the sum of the squares of departures of Y from the curve are as small as possible. The parameters used to judge the best fit were the coefficient of determination, the correlation coefficients, and the standard error of estimate. It was necessary to observe all the parameters and not just one in order to find the best fit. The basic equation referred to in the following discussion is:

$$Y = a + b \cdot f(X) \tag{6}$$

The coefficient of determination (r^2) shows the proportion of original variation that has been accounted for by the best fit line. In other words this is the proportion of variation in the values of Y (the dependent variable) which can be explained by the accompanying variation in values of X (the independent variable). The values of r^2 vary from zero to one with one being the case where all variation in Y can be explained.

The correlation coefficient (r) is equal to the square root of the coefficient of determination, and it shows the interdependence between Y and X. The values of r range from minus one to plus one. Minus one and plus one show a perfect correlation between Y and X, and the values of X will show all the variation in the values of Y. In the case of a straight line relationship the minus indicates a downward slope and the plus one an upward slope.

The standard error of estimate (SEE) indicates the closeness with which Y may be estimated by the values of X. It is computed from the standard deviation of the residuals in the ordinate-Y direction. In other words it indicates the amount of variation between the observed

Y value and the calculated Y value for the best fit curve. The better the fit of the curve, the closer is the value of the standard error of estimate to zero. For a value of zero all observed values of Y would fall on the best fit curve.

CHAPTER IV

PROCEDURE

As mentioned earlier three methods for collecting data were used during this study. During the collection of data at the two chosen sites, four traffic measurements were desired: mean speed, volume, density and truck percentage. The two test sites were located in the Atlanta Metropolitan Area.

Location of Sites and Areas

The first site considered was on the Northeast Expressway (Interstate 85) between Peachtree Street and Monroe Drive where the roadway consisted of two lanes in each direction. It was located about four miles from the State Capitol, which is located about four blocks from downtown, and about one mile from the Y-interchange of Interstate 75 and 85. Under normal conditions there was noticeable congestion of traffic at the site, and under peak-hour conditions there was considerable congestion with occasional stop-and-go situations. The grade considered, just beyond two railroad overpasses, was 2.75 per cent and 813 feet long (refer to Table 1 and Figure 1). It was about 3,400 feet beyond the Peachtree Street entrance ramp, and the Monroe Drive exit ramp was about 1,000 feet beyond the last area studied. The speed limit was 60 miles per hour.

One other site was selected for study. This site, between Coairmont Road and Shallowford Road, was chosen since its grade was about equal to the grade of the first site, 2.77 per cent, yet its length of grade was much longer, 3,400 feet long (refer to Table 1 and Figure 2).

Table 1. Physical Data on the Sites

Description	Peachtree	Shallowford
Pavement	Portland Cement Concrete	Asphaltic Concrete
Number of Lanes	4-Lane Divided	4-Lane Divided
Lane Studied	Outside Lane Outbound	Outside Lane Outbound
Lane Width	12 Feet	12 Feet
Median Width	14 Feet	40 Feet
Paved Shoulder Width	3 Feet	6 Feet
Posted Speed Limit	60 MPH	70 MPH
Physical Barriers (See Figures 1 and 2)	Overpass	-
	"Maintain Speed" Sign	

The site was also on the Northeast Expressway with two lanes of traffic in each direction, but it was about 11 miles from the Capitol. Preliminary observations noted considerable loss in speed, especially for heavy trucks, by the time the vehicle reached the top of the grade. The bottom of the grade, just before Peachtree Creek, was about 0.9

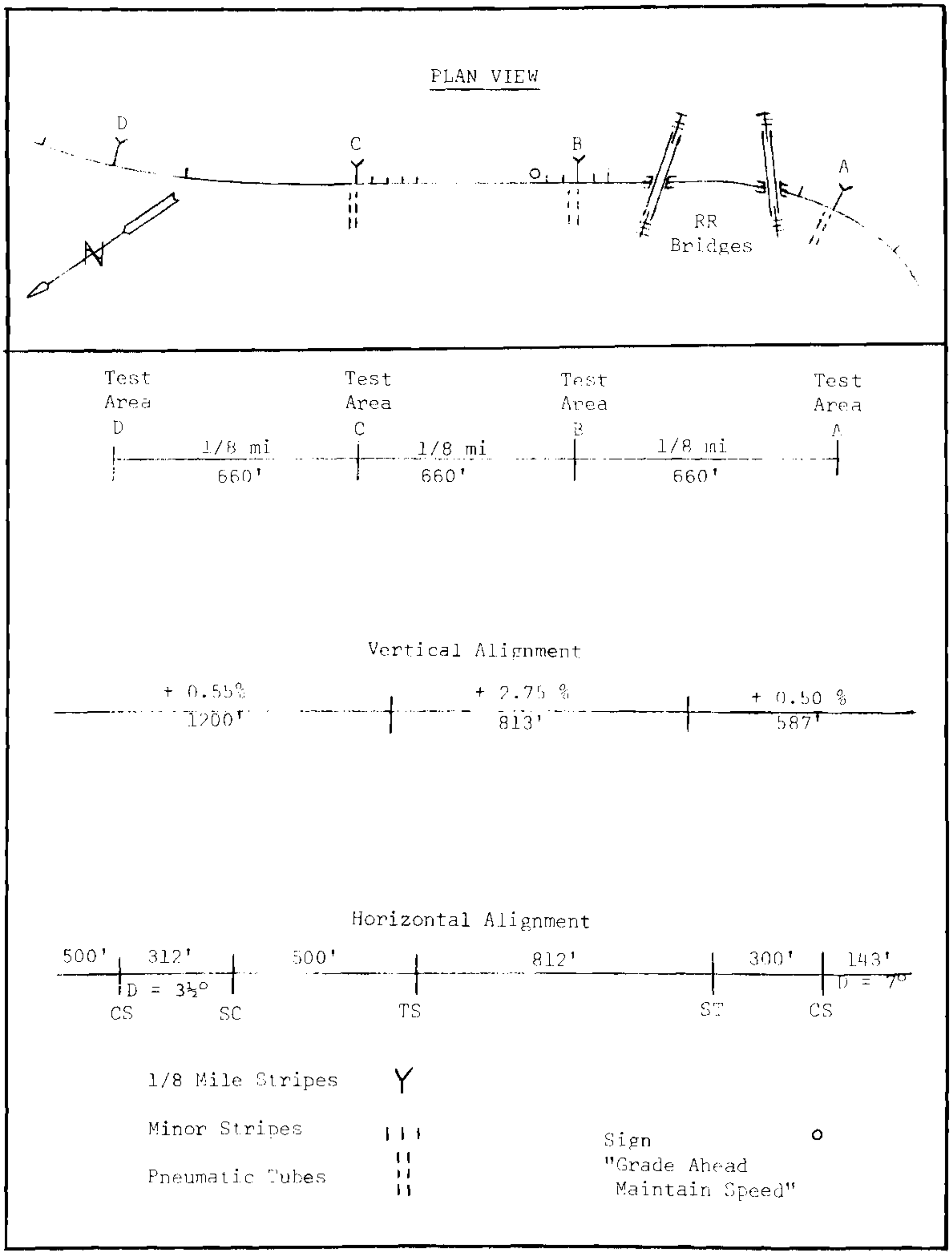

Figure 1. Peachtree Test Site

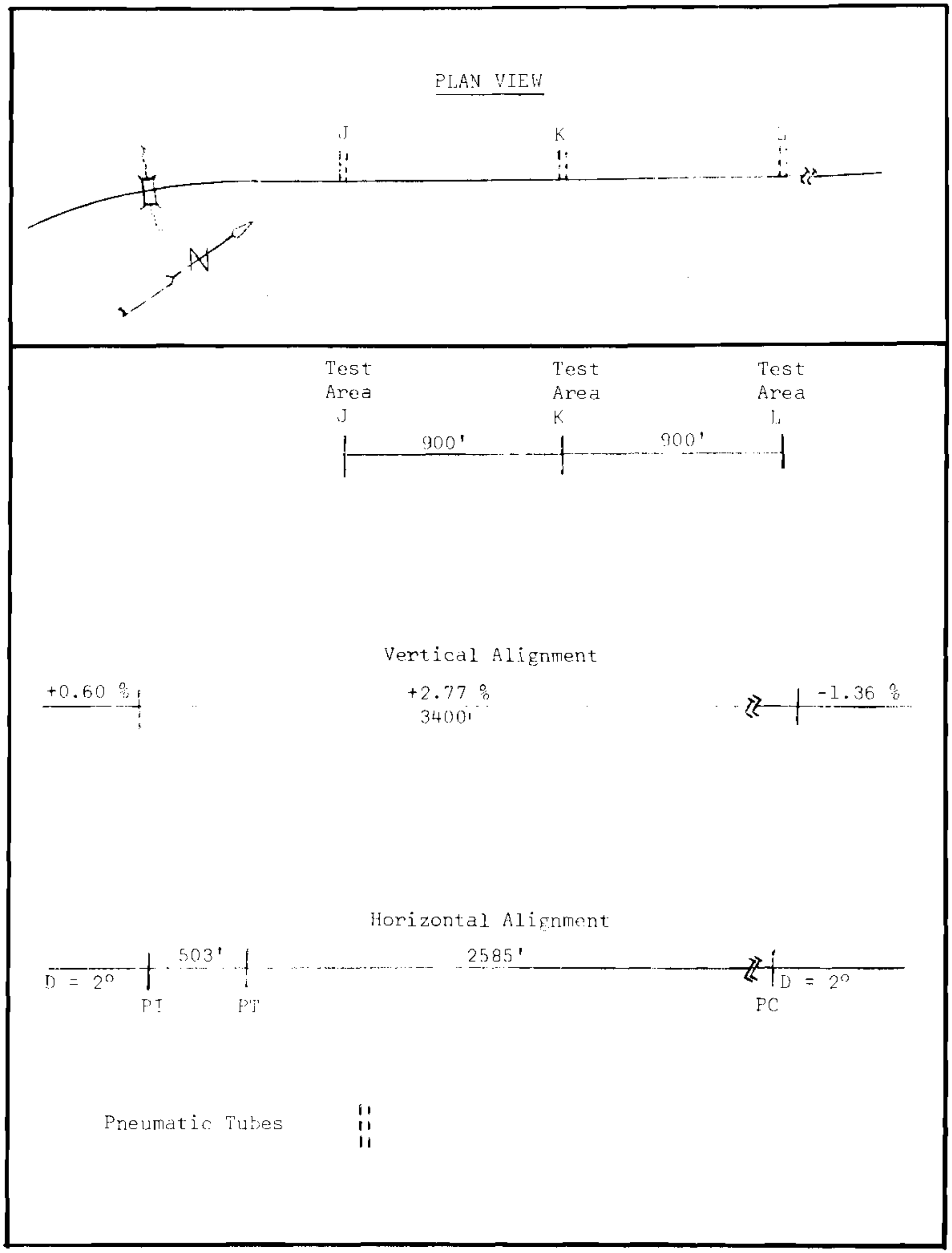

Figure 2. Shallowford Test Site

miles beyond the Clairmont entrance ramp. The Shallowford exit ramp occurred about 1,500 feet beyond the top of the grade. The speed limit was 70 miles per hour.

In location of test areas within the site, consideration was given to the original method of collecting data, that of flying. To determine the effect of length of grade it was necessary to have one test area at the beginning of the grade and one at the top of the grade. In order to tell the before-and-after effects two other test areas were located before the grade and after the grade. Ideally, these before-and-after test areas would be located on level ground and a tangent roadway. These would measure the quality of traffic flow under normal geometric conditions. Since aerial photographs were originally used, each of the four test areas were located 1/8 of a mile apart in order that density could more easily be determined.

Collection of Data

Test I

The first experiment was conducted at the Peachtree site. Two methods of data collection were used in this experiment: time-lapse aerial photography and time-lapse movies taken from a ground position overlooking the site. Speeds and density were the desired measurements to be obtained from the photographs. Time-lapse movies were taken to obtain the measurements of speed, volume and percentage of trucks. The use of these two methods provided a comparison for the speed measurements from the photographs. The time-lapse movies were taken simultaneously at test areas B and C.

Preparation of the site involved locating the four areas and placing markings on the pavement. Through the use of the construction plans, the areas were located to meet the previously described requirements and referenced from the second bridge for location in the field. Markings, which were painted on the shoulders of the freeway, consisted of four major, 1/8 mile stripes for measuring density as shown in Figure 1. At the before-and-after areas two reference stripes were placed 200 feet on each side of the major stripe to eliminate the need for photographic scaling. At the two middle areas, where the movie cameras were located, four additional stripes, spaced at 40 feet, were placed next to the major stripe. These were used for measuring speeds by the time-lapse movies.

It was decided to run the movie cameras for five minute intervals. C. J. Keese, C. Pinnell, and W. R. McCasland, in a 1960 report (21), stated that a five-minute time interval was a reasonable method for obtaining freeway traffic volumes. They also stated that this interval may *not* show extreme poor operating conditions which may be encountered when the capacity is exceeded. This allowed eight periods of five minutes duration on one roll of film. To allow the plane to circle and return to the site, the movie cameras were run for five minutes and stopped for five minutes. This resulted in the plane making the run over the site while the movie cameras were being run. Synchronization was accomplished by using citizen-band radios and synchronized watches.

Individual speeds were obtained from the photographs by measuring the distance a vehicle travelled during the interval between photographs. The time interval between photographs was determined from a clock with a second-hand located in the camera and next to the negative frame. Density was measured by counting the number of vehicles between the 1/8 mile stripes.

The trial run was made on Tuesday, May 9, 1967, between 4:15 and 5:30 PM. Only peak-hour measurements were obtained. The weather was clear, and therefore it had little effect on the flow of traffic. Since there was a strong wind, the plane flew into the wind and against the flow of traffic being studied. This reduced the plane's ground speed to about 120 miles per hour. The overlap for the photographs was set at 80 per cent, the maximum setting.

Test II

By mid-June Test I had been analyzed, and plans had been made for additional experiments. Unfavorable weather precluded the use of aerial photography in subsequent tests, therefore it was decided to change the method of collecting data to that of using a 20-pen event recorder and pneumatic tubes.

To make Test I meaningful, the event recorder and pneumatic tubes were located at each of the four original test areas within the Peachtree test site. Since equipment was limited, the tubes were placed only on the outside lanes. It was assumed that the worst condition of traffic flow would occur on the outside lane, since this was where the trucks usually travelled. Only speeds were obtained from the event recorder, therefore it was necessary to manually count the vehicles and the trucks during the five-minute periods. These volume counts were made for each lane, but only at the location of the event recorder.

The density would be calculated from the volume and the mean speed. The runs for obtaining data were spaced from mid-afternoon to evening according to the flow of traffic, thus getting measurements for different traffic conditions which included the peak-hour movements.

Knowing that stop-and-go situations would occur, it was decided to make the spacing of pairs of tubes as small as possible, yet large enough to be able to record speeds of around 80 miles per hour. The distance of 22 feet between the rubber tubes was chosen. After much difficulty eight diaphragms were obtained for the four test areas. Also sufficient electrical wire (18 gage, 2 chord) was obtained to connect the four areas (the diaphragms) to the centrally located event recorder. Due to faulty equipment and difficulty in obtaining additional parts, only three areas were studied. It was decided to choose the first three test areas for collecting data. There was more interest in the change of speeds of vehicles before the grade rather than beyond the grade, since it was assumed that eventually the speed of the vehicles beyond the grade would return to normal speeds.

Each rubber tube was connected to a channel on the event recorder, therefore one trap consisted of two channels on the recorder. When a vehicle passed over a tube, the diaphragm closed, the electrical circuit was completed, and the recorder made a mark on the recording paper. When a vehicle entered the trap, a mark was made on one channel, and, when the vehicle left the trap, a mark was made on a second channel. The distance between these marks was a measure of the time interval in which the vehicle was in the trap. A two-axle vehicle made two marks on one channel, therefore every other mark would be a new vehicle.

A similar adjustment was necessary for vehicles of more than two axles.

It was desired to obtain a mean speed of plus or minus two miles per hour. Knowing this and that the individual speeds might be as fast as 80 miles per hour, it was necessary to run the event recorder at a rate of three inches per second. Measurements on the roll of recording paper were then made to 0.1 inches and interpolated to 0.01 inches (or to 0.003 seconds). One-hundred foot long rolls of chart paper were used which provided a maximum running time of 6-2/3 minutes for each roll of paper. This was longer than the desired five-minute intervals.

The actual test was made on Tuesday, August 15, 1967, between 3:40 and 8:30 PM. The weather was partially cloudy, but the pavement was dry. As stated earlier, the runs were taken depending on the flow of traffic. At peak-hours more runs were made, since this was the time most interested in this study. As the traffic became lighter, the runs were spread further apart. A total of 13 runs were made.

Test III

Test III was conducted at the Shallowford test site (Figure 2). This test was carried out in a similar manner to Test II which permitted a better comparison of the two test sites. The length of grade was 3,400 feet long, and, since the maximum testing length was 1,800 feet, the third test area was placed at the top of the grade. The second and first areas were placed at 900 feet and 1,800 feet, respectively, down grade from the crest. By the time the first area was reached by vehicles, 950 feet of the grade had been traversed. This was a distance just greater than the length of grade on the first test site.

Difficulty was encountered in attaching the rubber tubes to the pavement since it was asphaltic concrete. To insure collections of some data, the testing was begun as soon as the equipment was set up. Data were collected between 1:55 PM and 5:25 PM on Wednesday, August 30, 1967. Each run was five minutes long, and the 12 runs were staggered to provide a distribution in the size of the volumes. The weather was partially cloudy and hot.

Evaluation of Data

Several assumptions were made in order to simplify the evaluation of the data. It was assumed and verified later that the frequency distribution of the speeds was normal for all the time intervals studied. R. T. Underwood (4), in a 1961 report, suggested that the distribution of speeds actually becomes skewed and departs from normality as the density increases. The assumption of normality was needed for the statistical evaluations. In the statistical tests a confidence level of 95 per cent (alpha equal 0.05) was chosen.

The measurement of volume, in vehicles per five minutes, was converted to an hourly volume by multiplying by 12. G. Webb and K. Moskowitz (13), in a 1957 study, found that for high five-minute volumes a factor of 12 did not hold true in large metropolitan areas. In their study they found that Los Angeles had a value of 11 and Sacramento had a value of 9. Since the *Highway Capacity Manual* (16) only gave generalized values for this factor, a factor of 12 was assumed to be as good as another factor. It was also decided that the results would be more meaningful if the volume measurements remained in vehicles per hour rather than be converted to passenger cars per hour. The correct value for the ratio between trucks and passenger cars was not known, and the value probably varied throughout the test anyhow.

Similar to the volume measurements, the 1/8 mile density measurements taken in Test I were converted to vehicles per mile by multiplying by eight. A mean density was determined by averaging the densities measured between the four areas.

In the regression analysis it was assumed that the speed-density curve was linear. Recent research (1), (4) has indicated this relationship may be exponential, but to simplify the speed-volume relationship, a linear relationship was chosen. Because of this assumption, and knowing that volume equals density times speed, the speed-volume curve was parabolic. Two previous studies, A. D. May in 1961 (3) and A. F. Malo, et al., in 1960 (22), contained a discussion on using the above assumptions to simplify traffic studies.

By the use of Equation (1) discussed in Chapter III, a minimum sample size was determined for calculating the mean speeds. The confidence level was chosen as 95 per cent, and the permitted error was ±2.0 miles per hour. In 1963 J. C. Oppenlander (23) stated that the standard deviation on a four lane, urban highway was 4.88 miles per hour, and in general for any type of road it was 5.0 miles per hour. Therefore, 5.0 miles per hour was chosen as the estimated standard deviation. With the above values, the sample size was 24. A minimum sample size of 30 was chosen, since 30 was the minimum value allowed under any conditions.

CHAPTER V

RESULTS

In evaluating the mean speed, the speeds of each vehicle were calculated first, and the mean speed was then determined by dividing the sum of the individual speeds by the sample size. The mean speed calculated was a time-mean speed and not a space-mean which is necessary for the equation volume equals density times speed to be true.

In 1952 J. G. Wardrop (24) showed the following relationship between time-mean speed and space-mean speed:

$$\bar{u}_t = \bar{u}_s + \sigma_s^2/\bar{u}_s \tag{7}$$

where $\bar{u}_t$ = time-mean speed,

$\bar{u}_s$ = space-mean speed,

σ_s^2 = variance of the space-mean speed.

By using this equation, the time-mean speeds of Test I were converted to space-mean speeds. To make these calculations, it was necessary to assume that the variances of the time-mean speeds were equal to the variances of the space-mean speeds, which is not necessarily true.

This resulted in each space-mean speed being slightly smaller than its corresponding time-mean speed. The effect on the overall results was very small. Indeed, variations of this magnitude in the measured speeds could be caused by field errors and rounding-off errors.

In view of this, and since the variances of the space-mean speeds were not precisely known, it was decided that using the original time-mean speeds in subsequent calculations and analyses would be preferable to the use of space-mean speeds computed from Equation (7).

In drawing the three sets of graphs, i.e., speed-density, volume-density and speed-volume, it was apparent that the speed-volume and volume-density curves could not be drawn with much accuracy due to the limited data points and the limited range of the data. The most meaningful results were obtained from the speed-density graphs. Summaries of the data obtained in the three tests are found in Tables 4, 5, 6 and 7 in the Appendix.

A linear relationship was assumed between speed and density. Linear regression was applied to the data for each area in each test (Figures 3, 4, 5). In most cases the standard error of estimate was between two and three miles per hour, and the coefficient of determination above 0.85. Table 7 is a summary of the regression analysis.

The "F-test" and the "t-test" indicated that the mean speeds measured at areas A, B and C and J, K and L in Tests II and III, respectively, could not be shown to be different (Table 2). In Test I, only the speeds measured at areas C and D were shown not to be different. It should be noted that Test I indicated that the data taken at areas A, B and C are significantly different whereas this difference was not shown by Test II. This indicates that significant shifts may occur in the speed-density curve within a short distance when the traffic volume is near capacity. These shifts were not noted at lower traffic volumes at either the Peachtree or Shallowford sites.

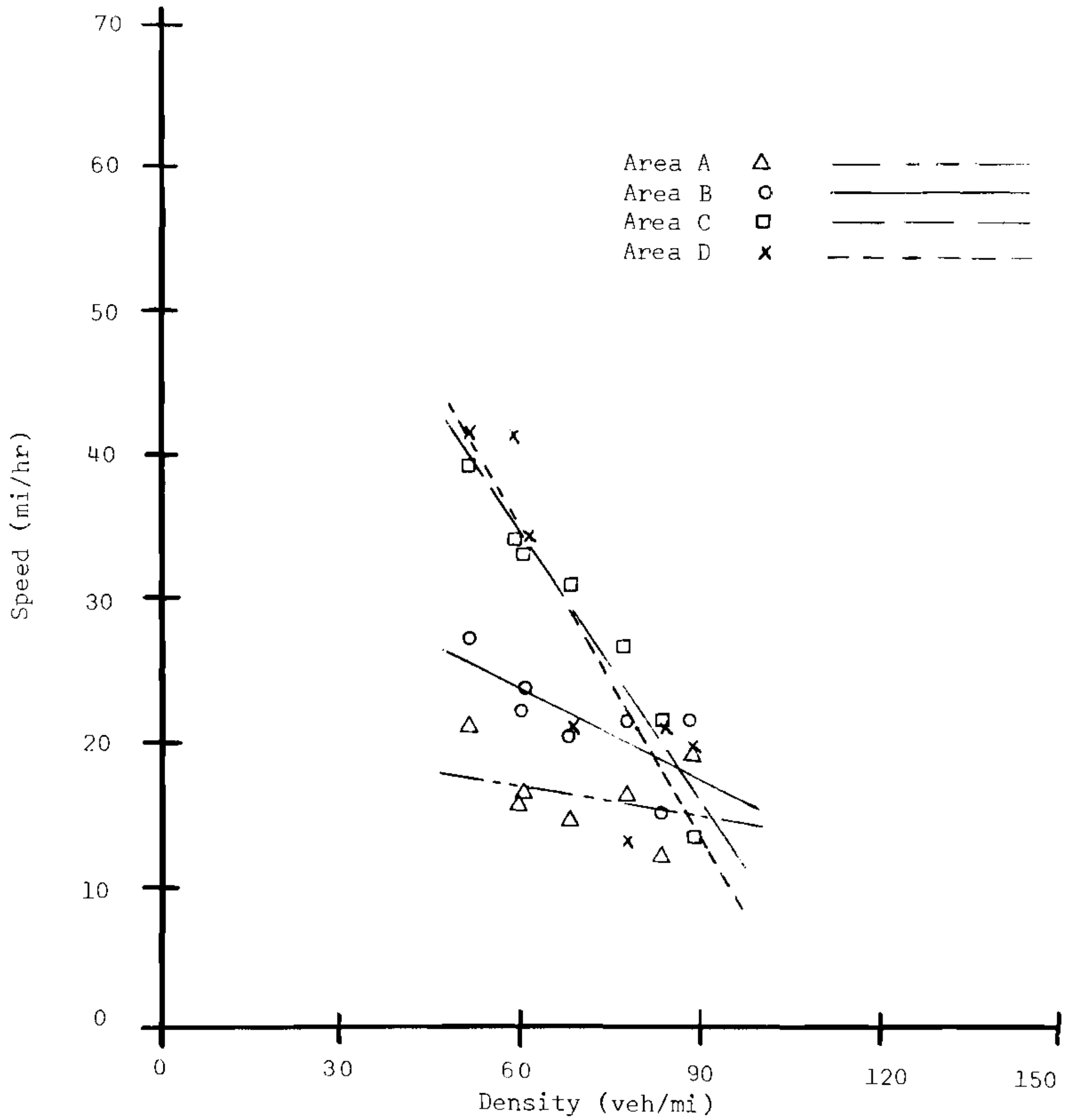

Figure 3. Relationship of Speed and Density for the Peachtree Test by Aerial Photography

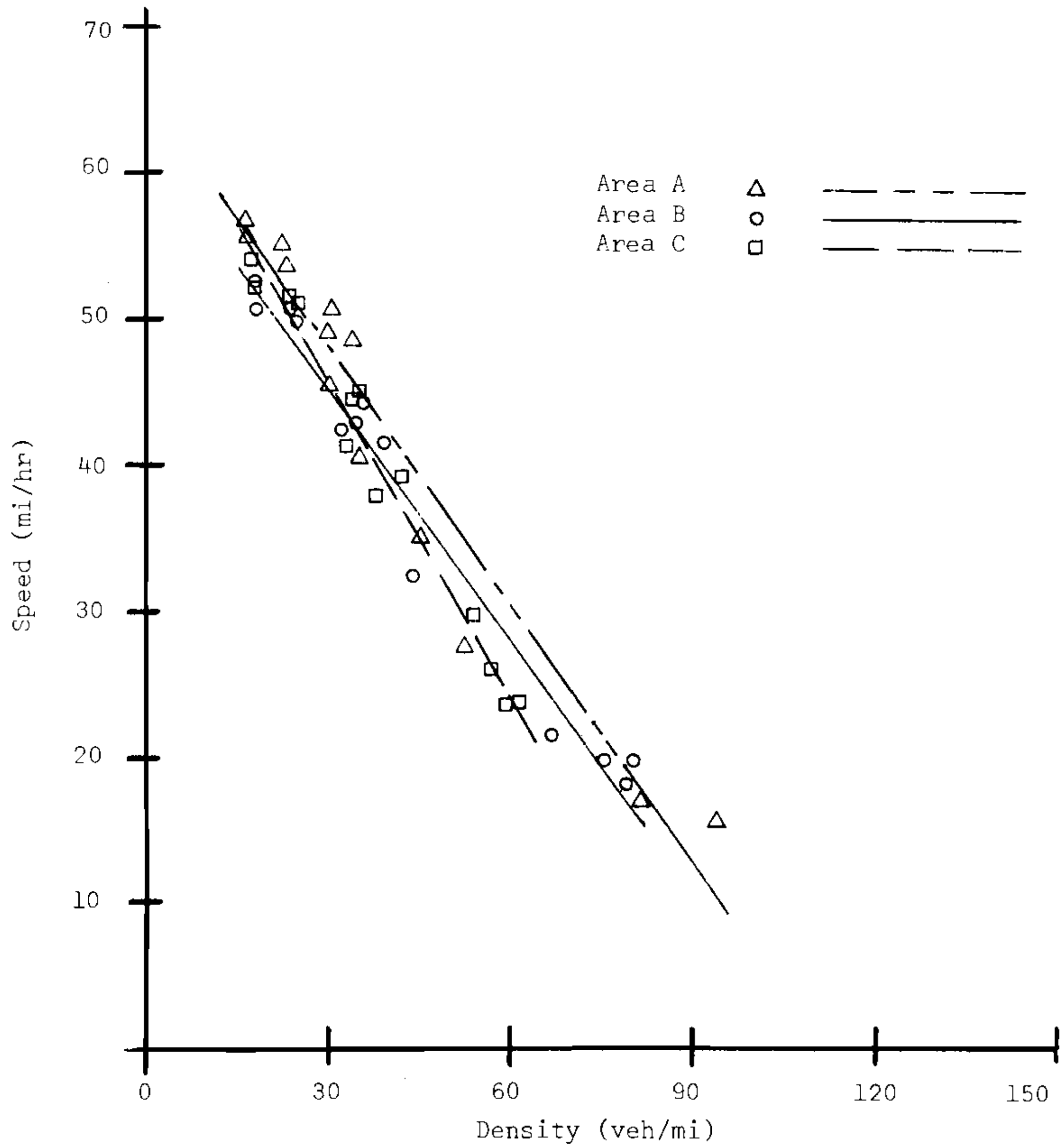

Figure 4. Relationship of Speed and Density for the Peachtree Test by 20-pen Event Recorder

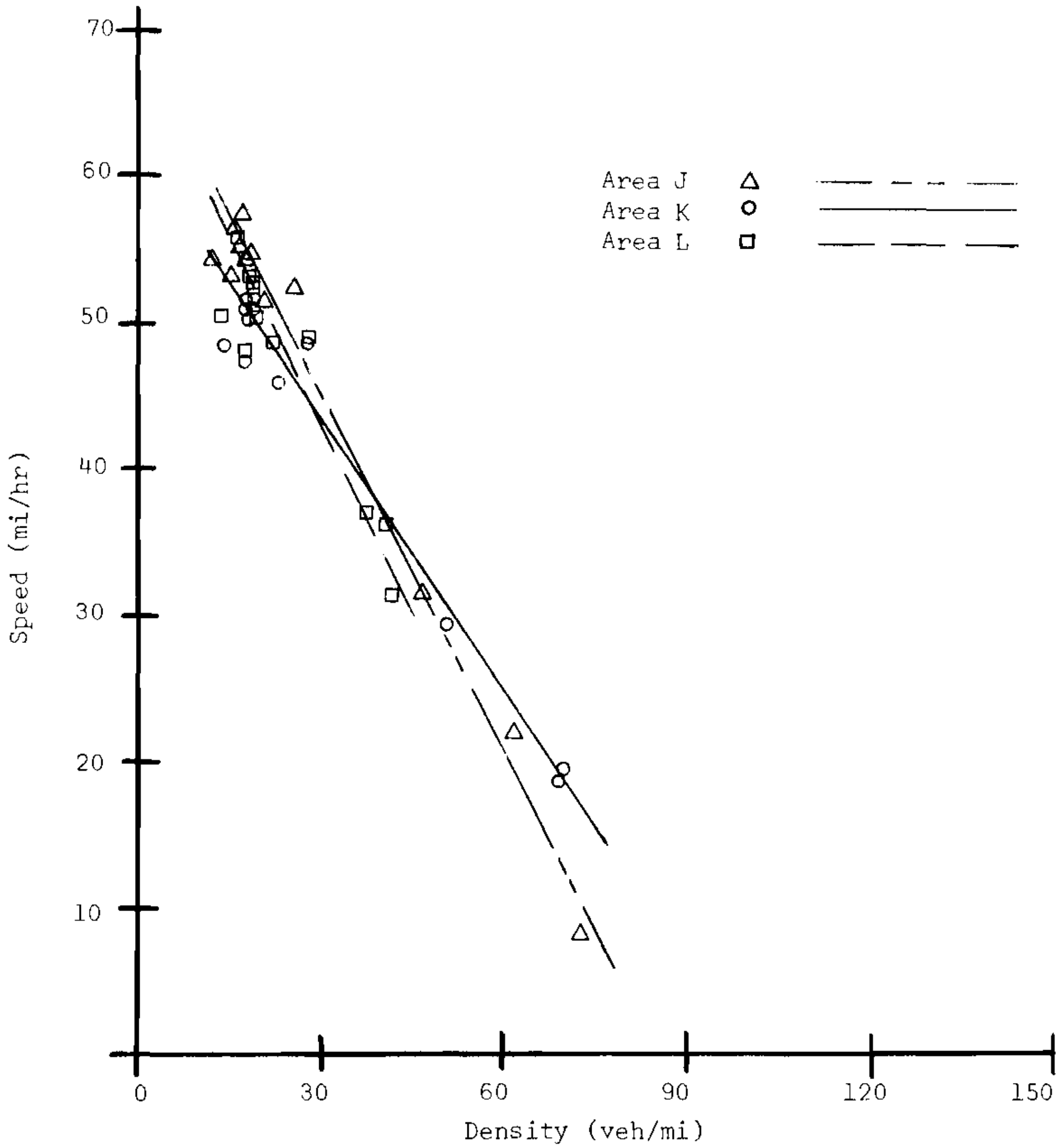

Figure 5. Relationship of Speed and Density for the Shallowford Test by 20-pen Event Recorder

Table 2. Tabulation of F-Test, T-Test and Paired Observation Test Results for Vehicle Speeds

Area vs Area		"F"	Accept	"T"	Accept	"PO"	Accept
Peachtree Trial Test							
A	B	8.46	NO	-4.99	NO	-8.04	NO
A	C	66.88	NO	-4.26	NO	-4.88	NO
A	D	97.90	NO	-3.26	NO	-3.64	NO
B	C	7.90	NO	-2.27	NO	-3.74	NO
B	D	11.57	NO	-1.65	YES	-2.44	NO
C	D	1.46	YES	0.21	YES	1.53	YES
DF		8,8		16		8	
Test Value		4.43		2.12		2.31	
Peachtree Test							
A	B	1.15	YES	0.92	YES	4.02	NO
A	C	1.64	YES	0.49	YES	1.70	YES
B	C	1.43	YES	-0.53	YES	-2.73	NO
DF		12,12		24		12	
Test Value		3.28		2.06		2.18	
Shallowford Test							
J	K	1.30	YES	0.75	YES	6.64	NO
J	L	3.39	YES	-0.07	YES	-0.16	YES
K	L	2.61	YES	-1.04	YES	-2.78	NO
DF		11,11		22		11	
Test Value		3.48		2.07		2.20	

Alpha = 0.05 for a two-tailed test.

F Hypothesis: Variances of the sets are the same.

T Hypothesis: Means of the sets are the same.

PO Hypothesis: Differences of individual values are the same.

These findings are consistent with the conclusion made by Legarra (14) that traffic flow is sensitive even to low grades when the traffic volumes approach the street capacity. It is possible, however, that these differences are not due to grade but to other roadway conditions, such as curvature or lateral obstructions, both of which were present at the Peachtree site.

As mentioned earlier, certain researchers have suggested that the speed-density relationship is really negative-exponential and not linear. To investigate this proposal, the data for Test II and Test III were plotted on semi-log graph paper. Since the areas were statistically the same, the sets of data from each test were considered to have come from the same population. The graphs (Figures 6,7) resulted in approximately straight lines. If converted back to rectilinear graph paper, these curves would be in the form of a negative-exponential curve.

With some degree of reliability the volume-density graphs (Figures 8,9,10) indicated that the peak volumes were about 1,650, 1,600 and 1,500 vehicles per hour per lane for Test I, Test II and Test III, respectively. Using 2,000 passenger cars per hour per lane as the ideal capacity for the expressway, the adjusted volume as calculated from the *Highway Capacity Manual* (16) was about 1,700 vehicles per hour per lane for both sites. This was found by using a truck percentage of 5 per cent. Test I, which had the lowest speeds, had traffic flowing near capacity. Test II had volumes that were slightly less than Test I which would account for the higher speeds. Test III, being further out from the center of the city, had the lowest volumes and highest speeds.

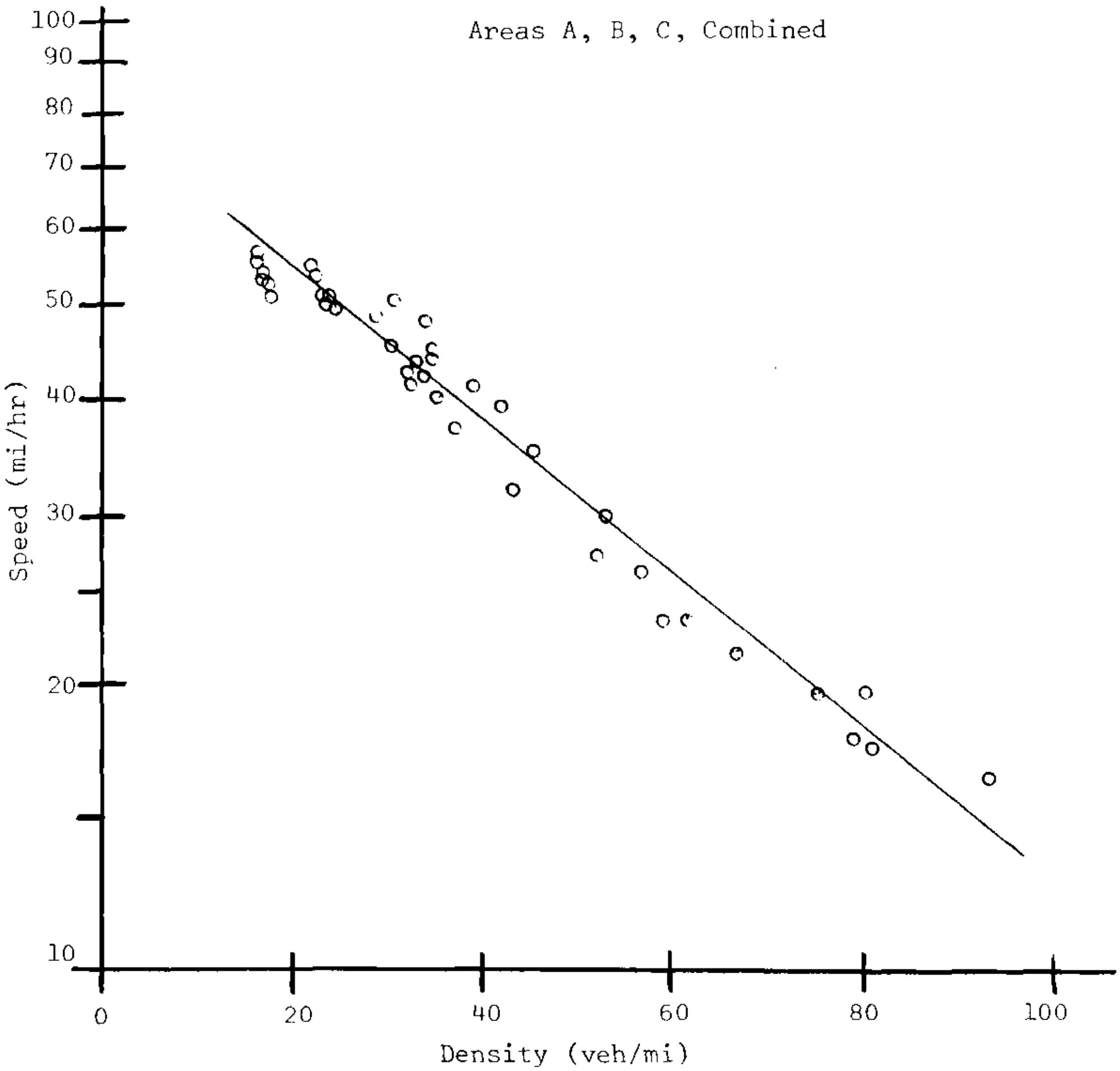

Figure 6. Relationship of Speed and Density for the Peachtree Test by 20-pen Event Recorder (Exponential)

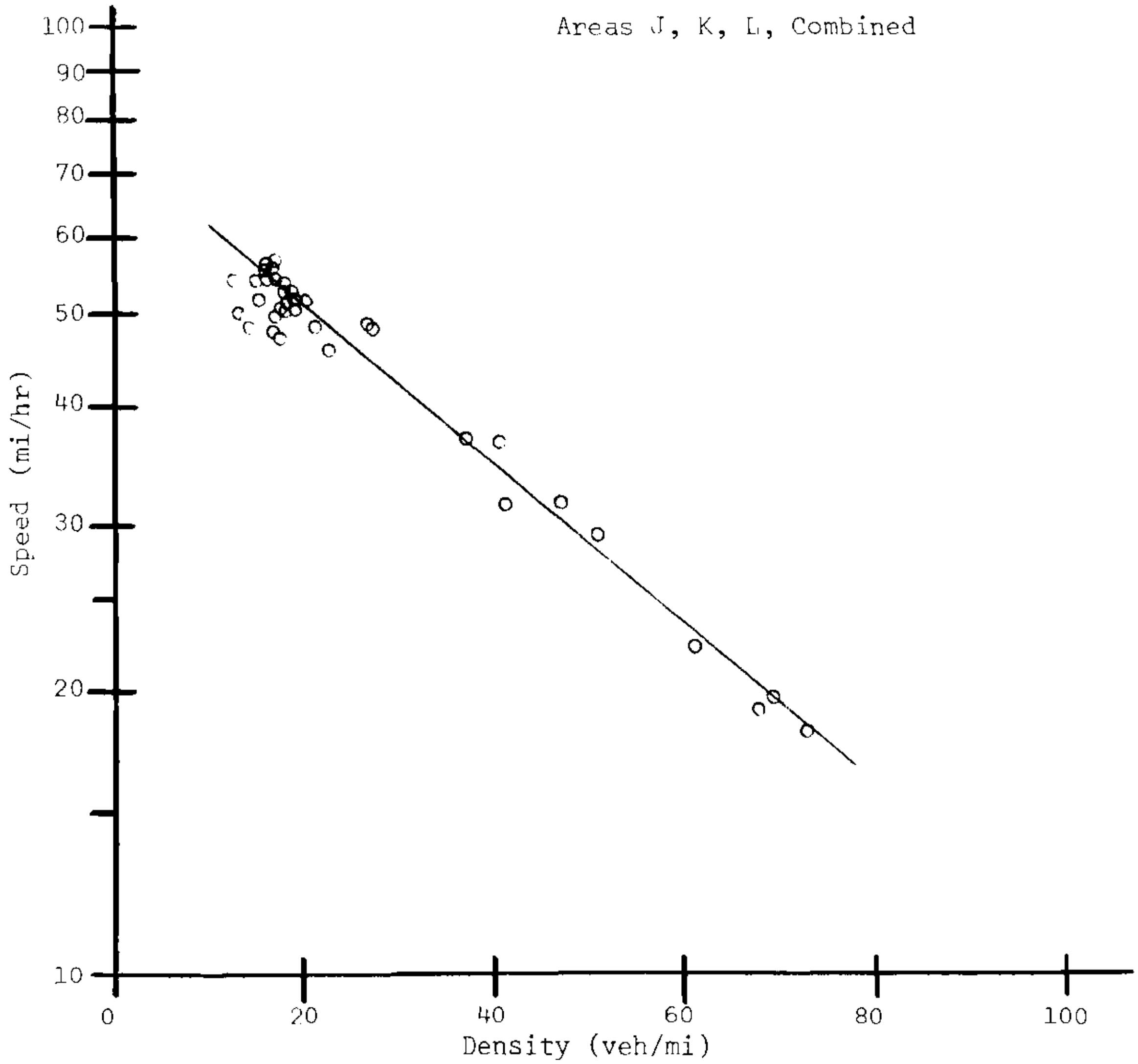

Figure 7. Relationship of Speed and Density for the Shallowford Test by 20-pen Event Recorder (Exponential)

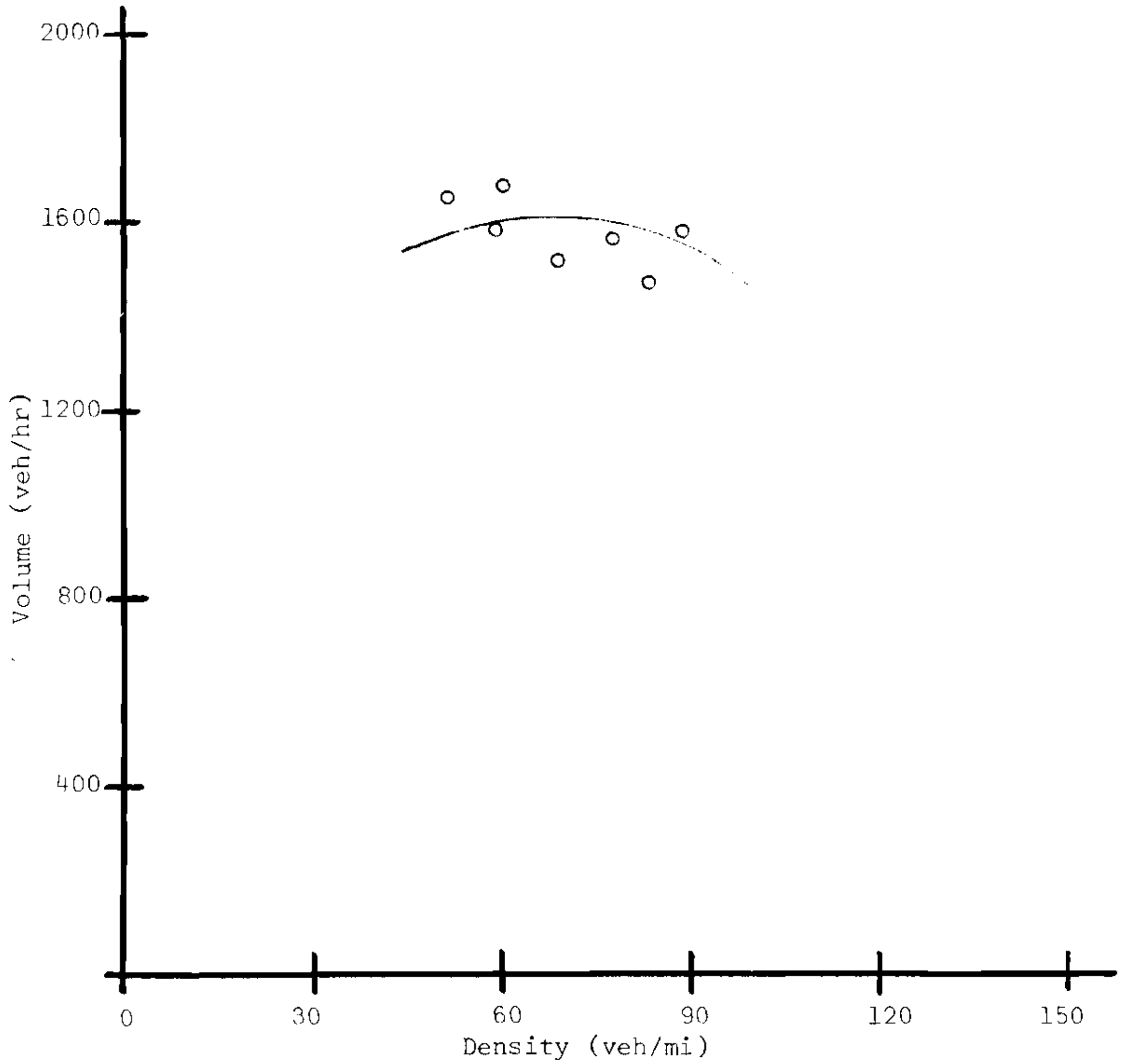

Figure 8. Relationship of Volume and Density for the Peachtree Test by Aerial Photography

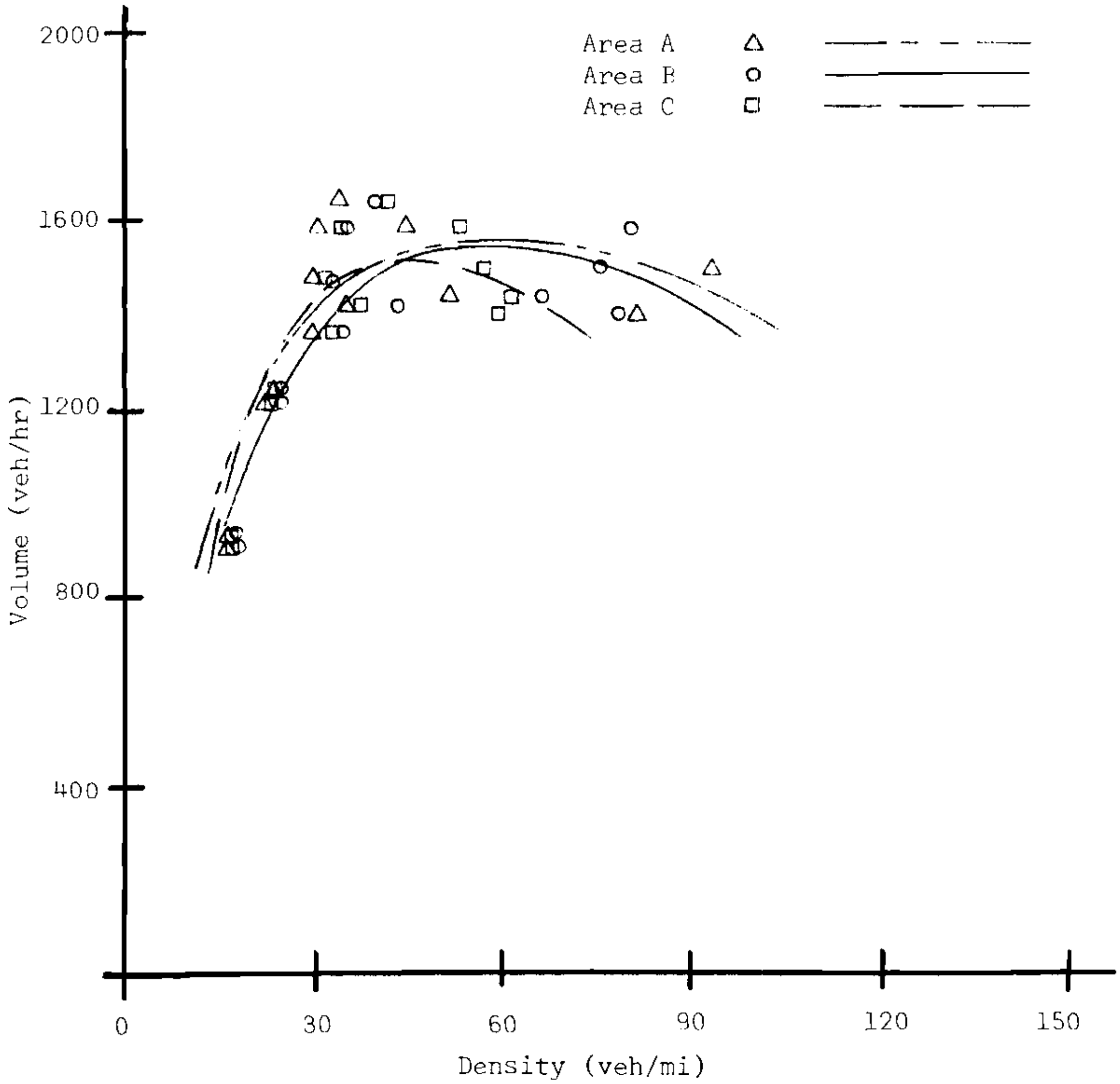

Figure 9. Relationship of Volume and Density for the Peachtree Test by 20-pen Event Recorder

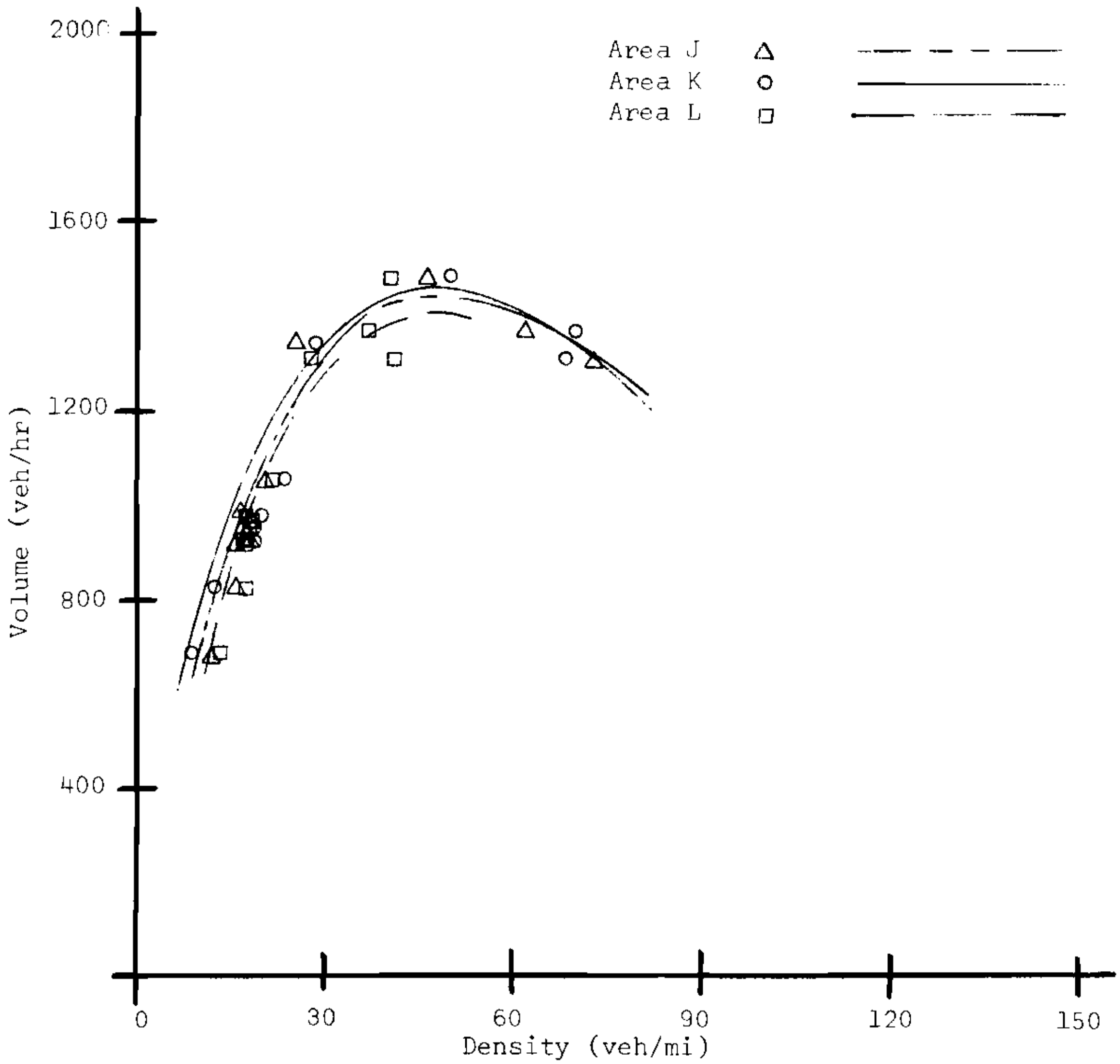

Figure 10. Relationship of Volume and Density for the Shallowford Test by 20-pen Event Recorder

The speed-volume graphs (Figures 11,12,13) were drawn free-handed. These graphs give an indication of the level of service as described by the *Highway Capacity Manual* (16) at which the traffic was operating. Test I was flowing at levels E and F, or unstable and forced flow. Test II ranges from level C to F, or from stable flow to forced flow. Free flow might have been encountered in Test III, but there was forced flow also (range of levels from A or B to F). The forced flow conditions occurred when the traffic was moving at a "stop-and-go" rate. These periods are indicated in Tables 4, 5, 6 and 7.

To test the validity of the assumption that vehicle speeds were normally distributed, one set of data for a five-minute period from each of the three tests were tested by the Chi-Square Goodness of Fit Test. Table 3 shows that the tests resulted in the data being not significantly different from the normal distribution. Since mean values of the vehicular speeds were tested, it should be noted that according to the Central Limit Theorem no matter what the shape of the population distributions, the distributions should have tended towards normality. Histograms of the three tests are included in the Appendix (Figures 14,15,16). As previously done, the areas were combined as a unit when they had been statistically shown to be the same.

The relationship between mean speeds and percentage of trucks was also graphically shown (Figures 17,18,19). For all three tests there appeared to be no relationship between mean speeds and percentage of trucks. It was interesting to note that in Test III the mean speeds ranged between 47 and 57 miles per hour for truck percentages over 6 per cent.

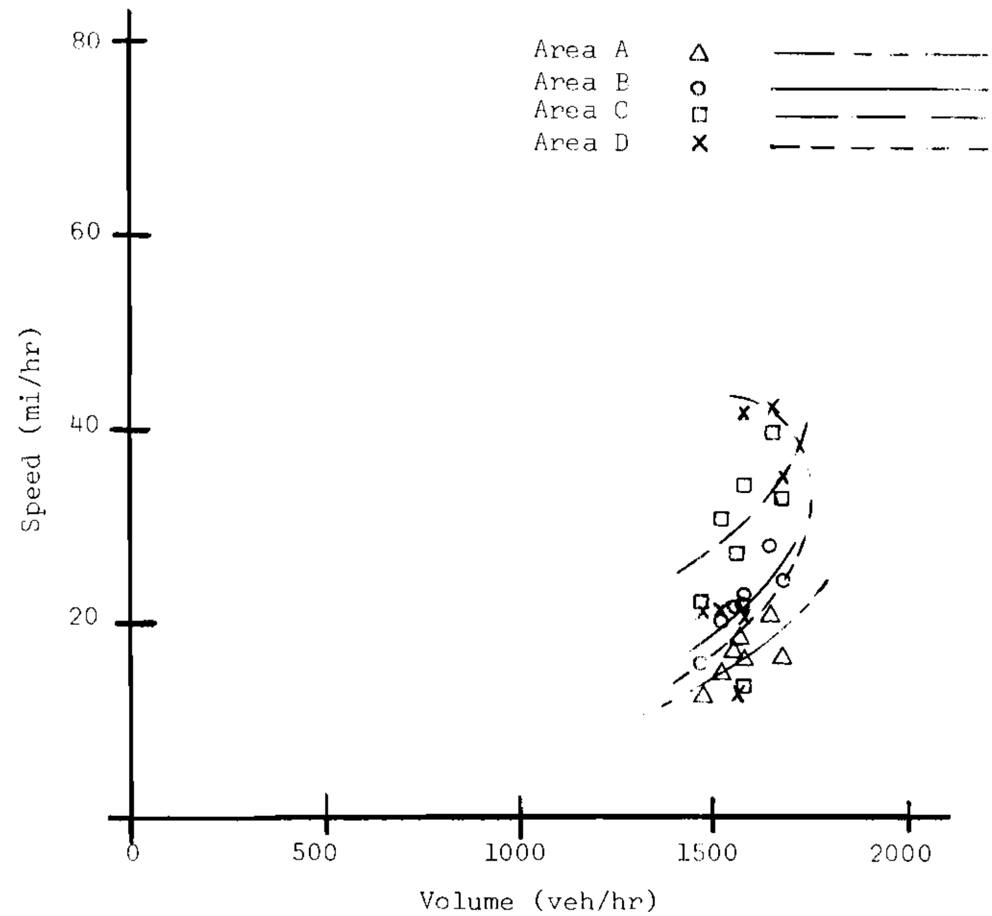

Figure 11. Relationship of Speed and Volume for the Peachtree Test by Aerial Photography

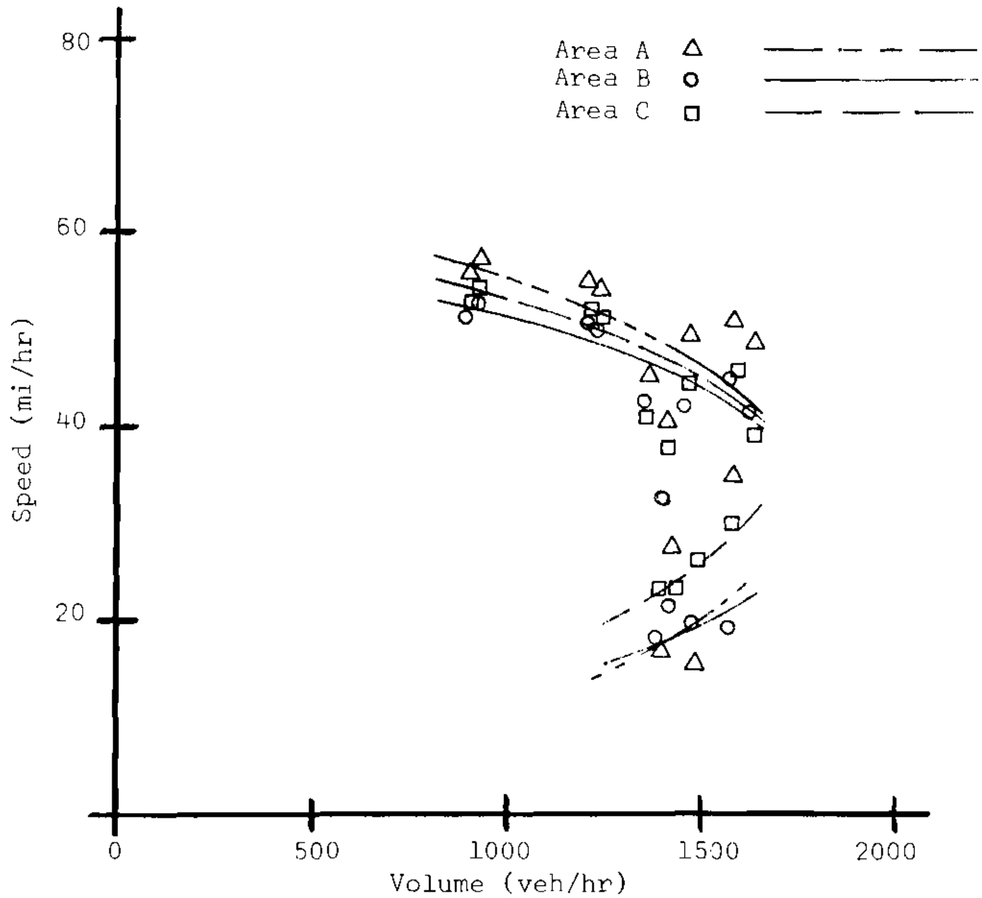

Figure 12. Relationship of Speed and Volume for the Peachtree Test by 20-pen Event Recorder

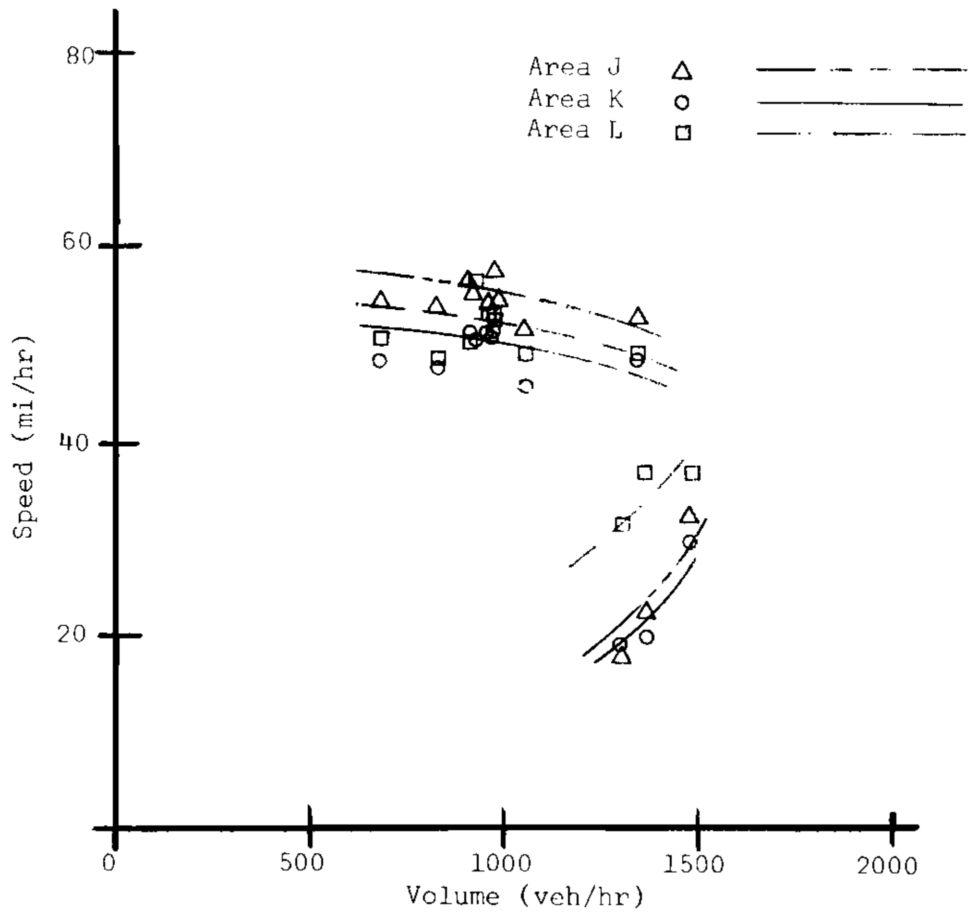

Figure 13. Relationship of Speed and Volume for the Shallowford Test by 20-pen Event Recorder

Table 3. Summary of the Chi-Square Goodness of Fit Test for a Normal Distribution of Speeds

Site Area	Sample Size	Number of Intervals (4 MPH)	μ (MPH)	σ (MPH)	χ^2 Calc.	χ^2 Table	Accept
Peachtree-1 4:55-5:00							
A	23	4	12.3	3.4	2.4	5.0	YES
B	18	3	15.3	3.1	0.9	?	-
CD	46	4	21.2	4.6	0.7	5.0	YES
Peachtree-2 3:50-3:55							
ABC	180	7	45.4	5.3	10.9	11.1	YES
Shallowford 4:00-4:05							
JKL	180	7	52.6	6.5	10.7	11.1	YES

Alpha = 0.05 for a two-tailed test.

Degree of Freedom = (Number of intervals - 3).

A Policy on Geometric Design of Rural Highways (17) gave the average running speed of vehicles under the given conditions as 54 miles per hour. This indicates that the traffic reached its maximum mean speeds on the long grade and with high truck percentage.

A question in Test I was whether the sample sizes were too small. A minimum of 30 vehicles is normally desired, yet out of the 28 sub-tests only one consisted of more than 30 vehicles. In 1958, Martin Wohl (25) suggested that an airplane going four times faster than a motor vehicle would require only one-quarter of the data as required by a standard ground procedure of collecting data. He also stated that research was needed in answering the question of sample size.

Not knowing the validity of using time-lapse aerial photography for obtaining vehicle speeds, the mean speeds calculated by time-lapse movies and by aerial photography for areas B and C were compared (Tables 4,5). Since it was possible to identify the same vehicle on both the movies and the photographs, the speeds of 22 vehicles were measured by methods, and the values were compared to see if they were the same. A paired observation test was made and resulted in the null hypothesis, that the differences between the speeds were zero, being accepted (Table 9).

CHAPTER VI

CONCLUSIONS

From the results of this research the following conclusions have been made:

1. The speed-density, volume-density and speed-volume curves may vary in position and shape when plotted by data taken at different closely-spaced test areas. On short courses it is possible to detect factors which contribute to changes in the level of service of the roadway by observing the variation in these graphs.

2. The results showed that under conditions of light to moderate traffic demand, the short length of grade had little effect on the quality of the traffic flow. This was true even when the percentage of trucks was relatively high. However, it was found that significant shifts in the speed-density curve may occur within a short distance when the traffic volume is near capacity.

3. For levels of service from B to D, the long length of grade caused heavy vehicles to lose speed, but the total flow of traffic was only slightly affected, since the faster moving vehicles could pass the slower moving vehicles. As levels E and F occurred, which was caused by the Shallowford interchange, all vehicles reduced their speeds at the first part of the grade. Due to the increasing headways at the top of the grade, speeds increased as the crest was reached.

4. Time-lapse aerial photography can be used effectively for measuring vehicle speeds and densities. There was question as to the effect on the final results of the small sample sizes obtained within a small area.

5. Time-lapse aerial photography permitted measures along the total course under study at nearly the same instant of time.

6. The results failed to indicate that the mean speeds were influenced by the percentage of trucks.

CHAPTER VII

RECOMMENDATIONS

The following recommendations are made concerning the study of the theory of traffic flow:

1. Additional investigation is necessary to determine the value and magnitude of the observed changes in the speed-density, volume-density and speed-volume graphs when plotted from data taken at different test areas within a short length of roadway.

2. Continued research is needed in determining the shapes of the speed-density, volume-density and speed-volume curves.

3. Further study is necessary to determine the effect of measuring mean vehicular speeds over relatively long lengths of roadway which occur in time-lapse aerial photography and to determine the minimum sample size for finding mean vehicular speeds by time-lapse aerial photography.

APPENDIX

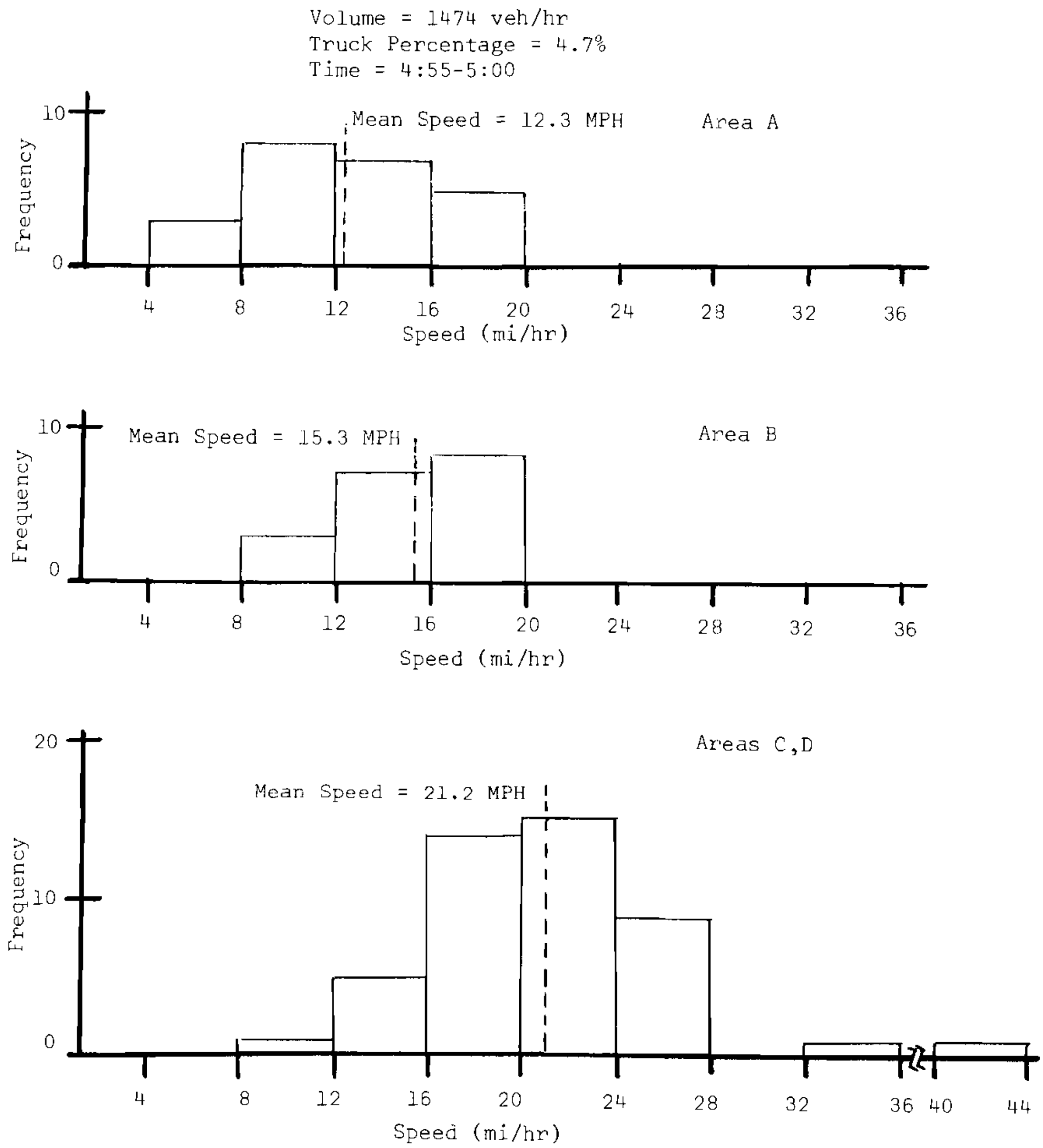

Figure 14. Histogram of Speeds for the Peachtree Test by Aerial Photography

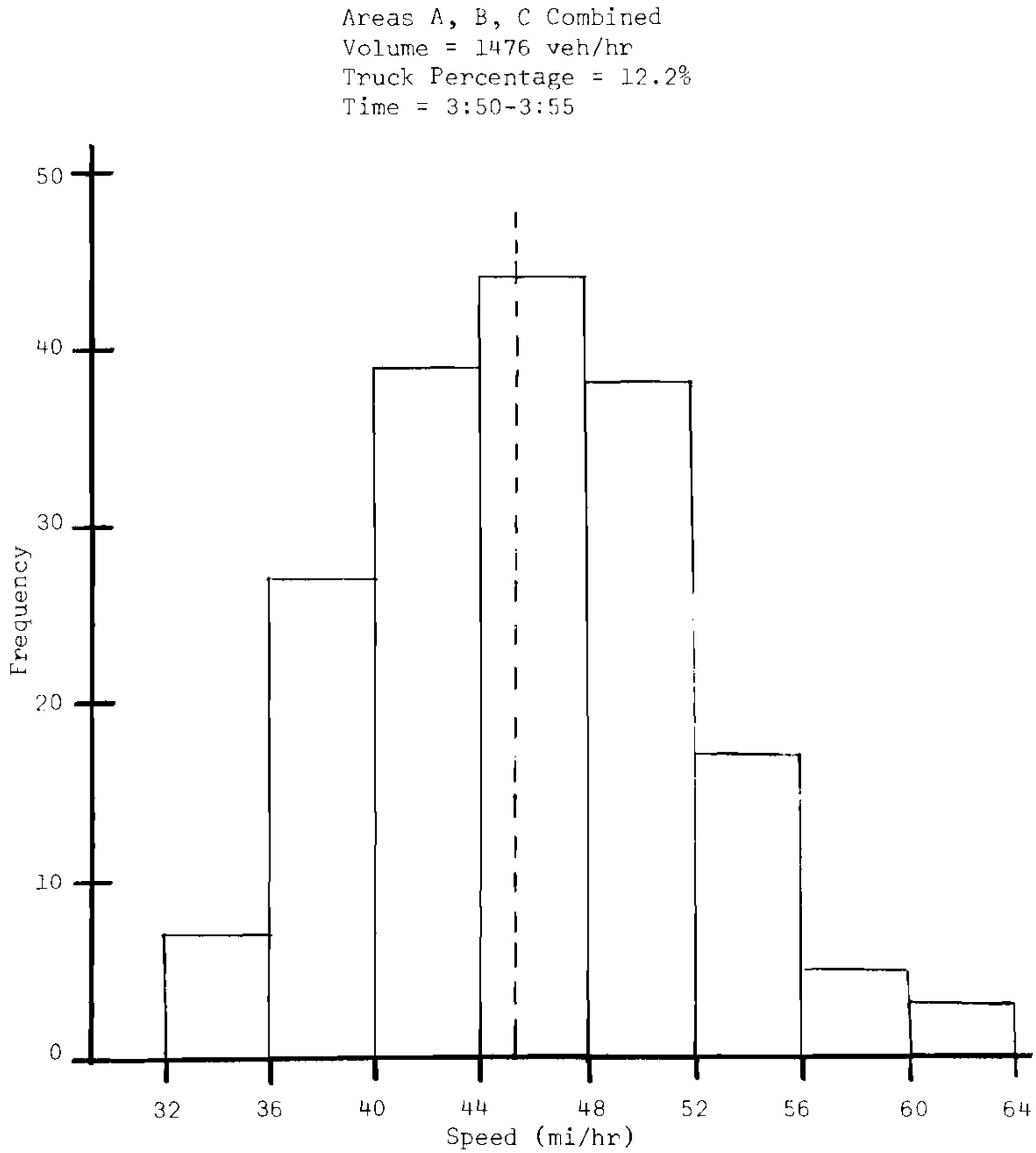

Figure 15. Histogram of Speeds for the Peachtree Test by 20-pen Event Recorder

Areas J, K, L Combined
Volume = 972 veh/hr
Truck percentage = 7.4 %
Time = 4:00-4:05

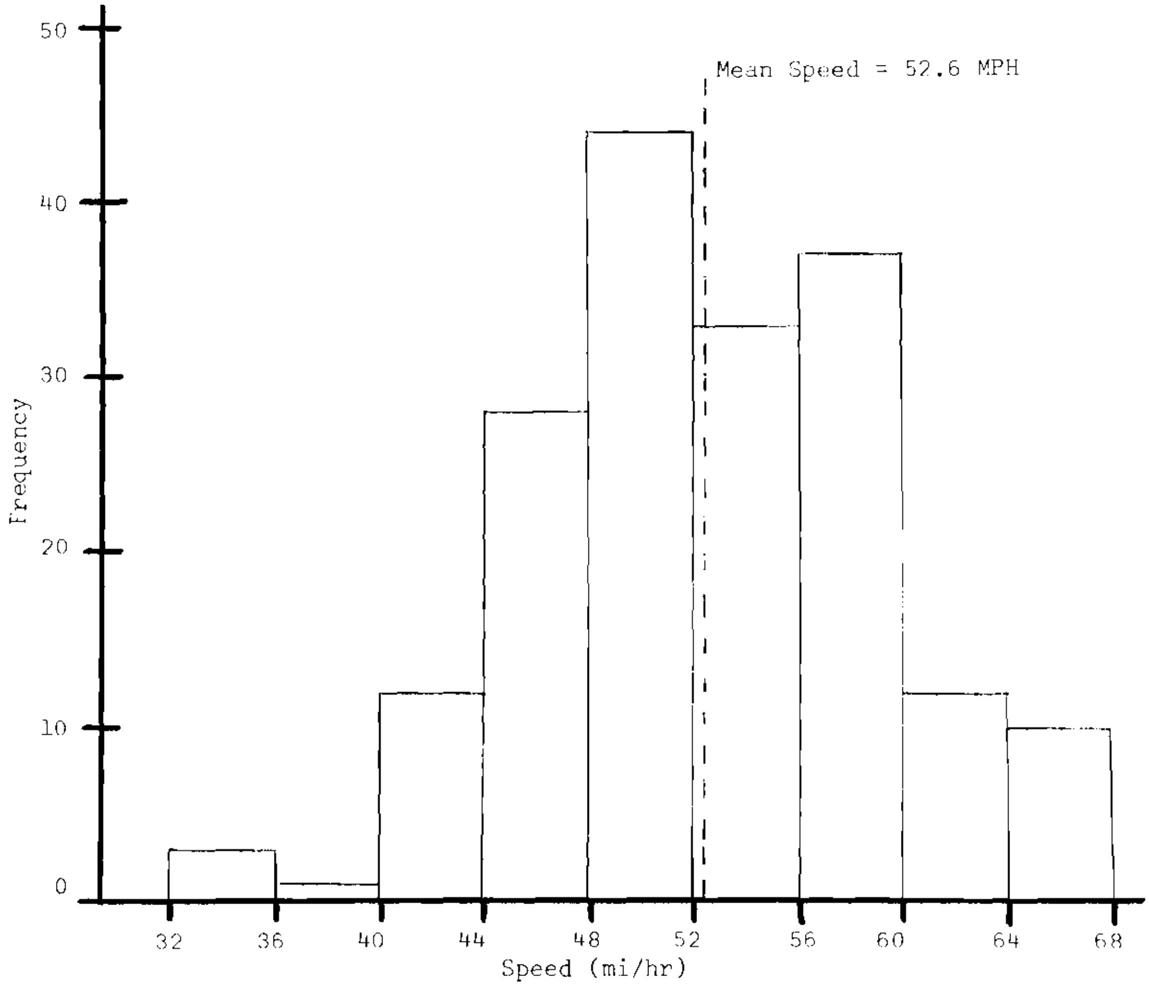

Figure 16. Histogram of Speeds for the Shallowford Test by 20-pen Event Recorder

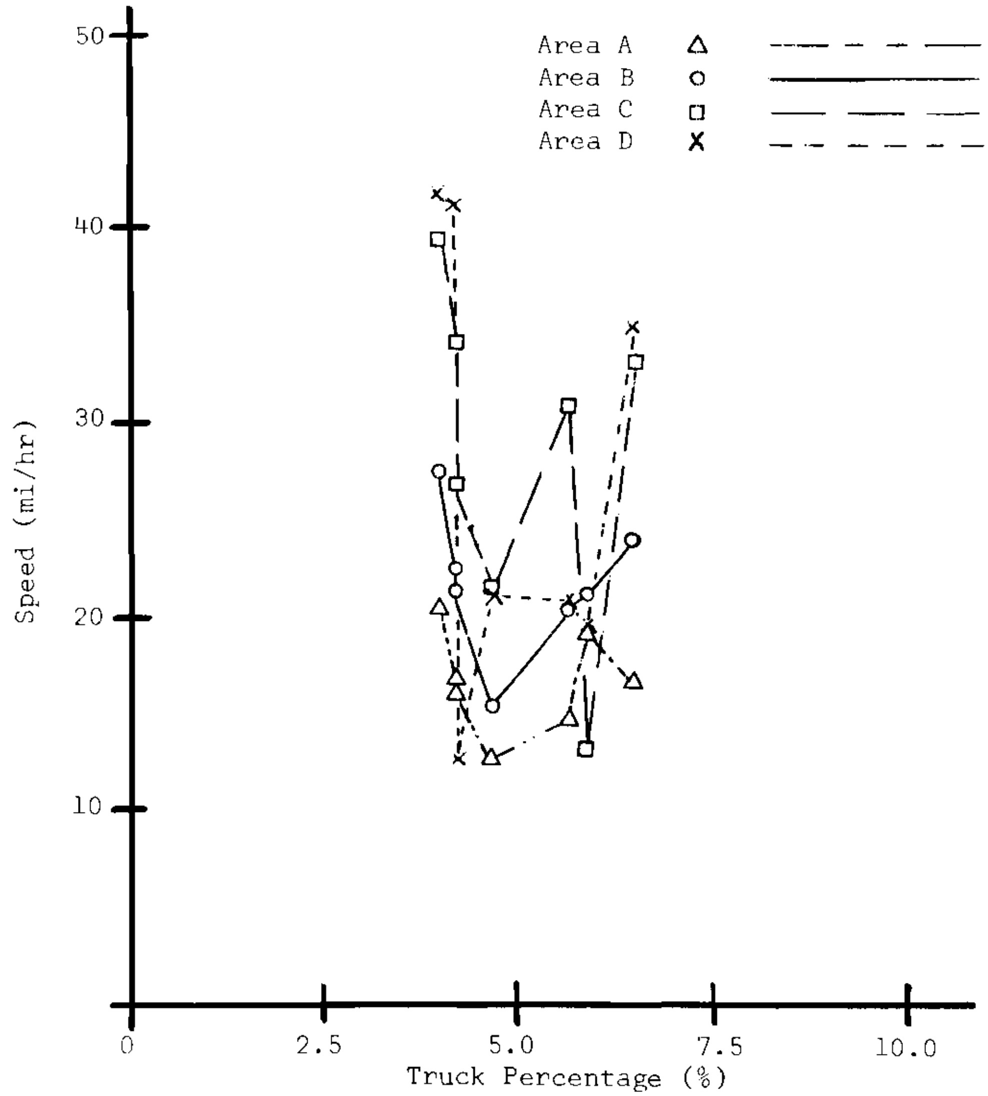

Figure 17. Relationship of Speed and Truck Percentage for the Peachtree Test by Aerial Photography

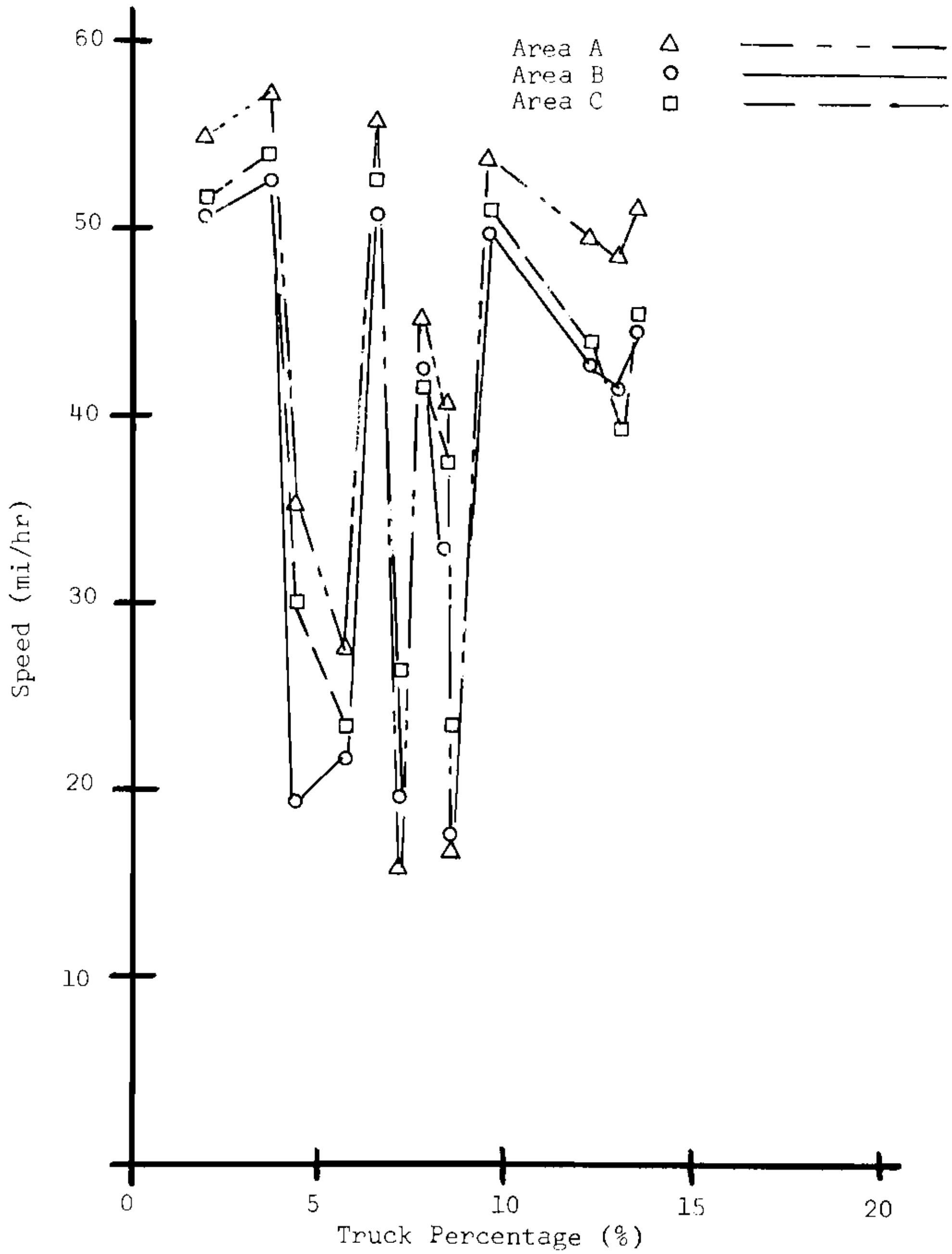

Figure 18. Relationship of Speed and Truck Percentage for the Peachtree Test by 20-pen Event Recorder

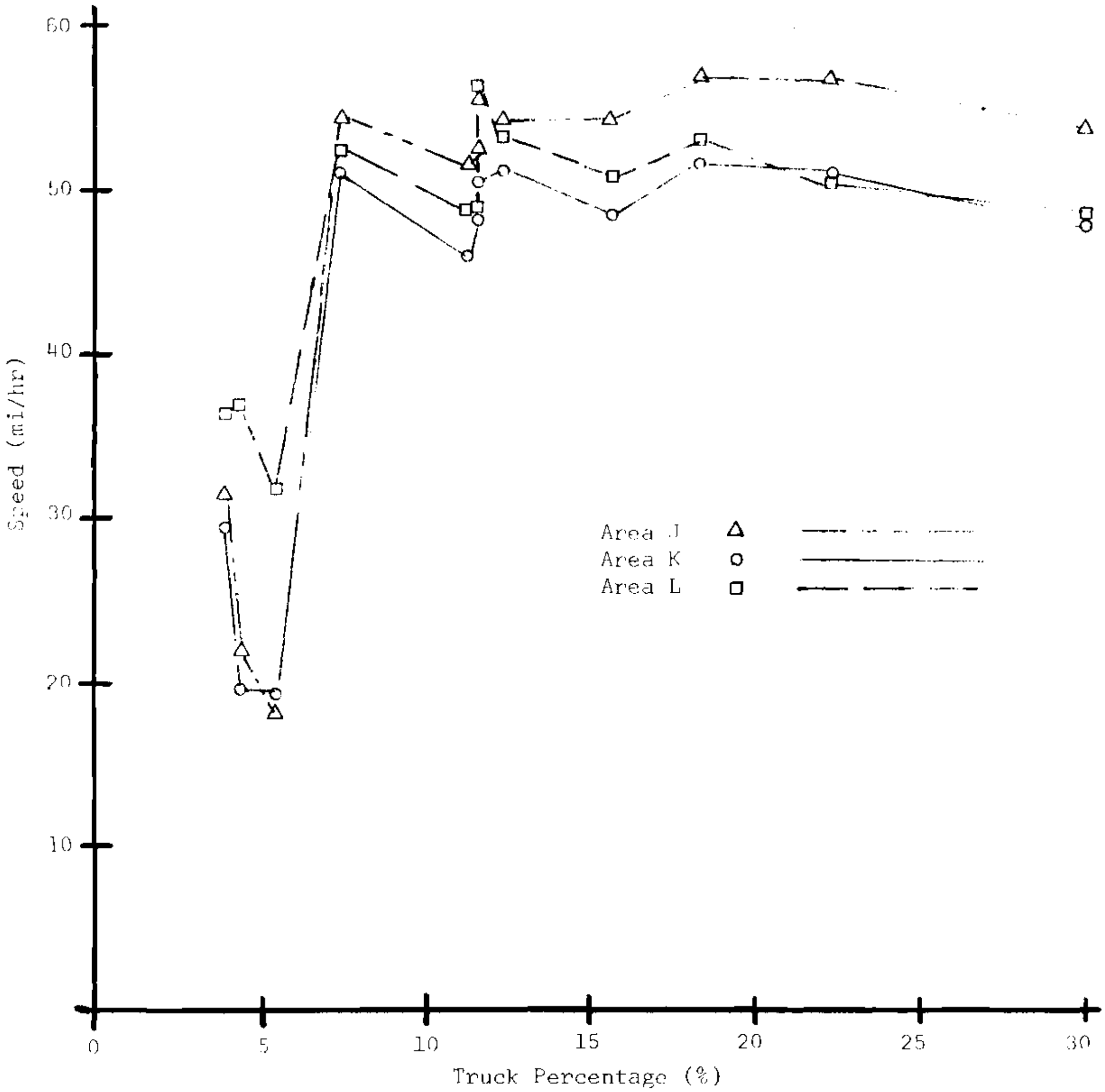

Figure 19. Relationship of Speed and Truck Percentage for the Challowford Test by 20-pen Event Recorder

Table 4. Tabulation of Peachtree-Monroe Data Taken on May 9, 1967, by Aerial Photography

	Time PM	Area	Volume Q veh/hr	Density K veh/mi	Mean Speed V mi/hr	Std. Dev. S mi/hr	Sample Size N	Truck Per Cent T %
1	4:15-4:20	A	1647	51.4	20.6	2.0	17	4.0
		B			27.4	1.7	11	
		C			39.3	4.2	7	
		D			41.9	3.1	12	
2	4:25-4:30	A	1677	60.7	16.3	3.5	23	6.5
		B			24.0	5.0	16	
		C			32.9	2.9	22	
		D			34.7	2.9	14	
3	4:35-4:40	A *	1580	88.8	18.8	4.5	23	5.9
		B			21.2	2.9	17	
		C			13.1	7.6	15	
		D			19.4	2.3	26	
4	4:45-4:50	A	1580	59.3	16.0	3.9	21	4.2
		B			22.3	3.2	16	
		C			34.0	5.1	13	
		D			41.6	4.0	21	
5	4:55-5:00	A *	1474	83.2	12.3	3.4	23	4.7
		B			15.3	3.1	18	
		C			21.4	2.6	19	
		D			21.1	6.6	27	
6	5:05-5:10	A *	1566	77.5	16.5	5.9	27	4.2
		B			21.1	3.4	18	
		C			26.7	3.2	16	
		D			12.7	3.5	33	
7	5:15-5:20	A	1526	68.4	14.6	5.1	21	5.6
		B			20.2	2.2	17	
		C			30.6	2.5	13	
		D			20.6	5.0	29	

NOTE:

(1) Volume per lane is average of two lanes and of two areas (movie camera).

(2) Density per lane is average of two lanes and of four areas (aerial photography).

(3) Mean Speed is average from two lanes (aerial photography).

(4) Sample Size is for calculating mean speed.

(5) Truck Per Cent per lane is average of two lanes and of two areas (movie camera).

* "Stop-and-go" conditions.

Table 5. Tabulation of Peachtree-Monroe Data Taken on May 9, 1967, by Time-Lapse Movies

	Time PM	Area	Volume Q veh/hr	Density K veh/mi	Mean Speed V mi/hr	Std. Dev. S mi/hr	Sample Size N	Truck Per Cent T %
1	4:15-	B	1647	51.4	25.2	5.2	37	4.0
	4:20	C			36.3	6.4	39	
2	4:25-	B	1677	60.7	25.4	3.7	52	6.5
	4:30	C			34.8	5.2	52	
3	4:35-	B *	1580	88.8	21.5	4.3	46	5.9
	4:40	C			24.2	7.3	50	
4	4:45-	B	1580	59.3	20.9	3.6	48	4.2
	4:50	C			33.6	4.7	50	
5	4:55-	B *	1474	83.2	19.2	4.1	44	4.7
	5:00	C			20.2	6.7	45	
6	5:05-	B *	1566	77.5	22.3	3.7	50	4.2
	5:10	C			24.7	7.7	47	
7	5:15-	B	1526	68.4	20.9	3.8	48	5.6
	5:20	C			26.3	6.7	50	

NOTE:

(1) Volume per lane is average of two lanes and of two areas (movie cameras).

(2) Density per lane is average of two lanes and of four areas (aerial photography).

(3) Mean speed is average from two lanes (time-lapse movies).

(4) Sample size is for calculating mean speed.

(5) Truck per cent per lane is average of two lanes and of two areas (movie cameras).

* "Stop-and-go" conditions.

Table [illegible]. Tabulation of Peachtree-Monroe Data Taken on August 15, 1967, by 20-pen Event Recorder

	Time PM	Area	Volume q veh/hr	Mean Speed V mi/hr	Density K veh/mi	Standard Deviation S mi/hr	Truck Percentage T %
1	3:40-	A	1584	51.0	31.1	3.5	13.6
	3:45	B		44.5	35.6	3.4	
		C		45.1	35.1	3.8	
2	3:50-	A	1476	49.4	29.9	5.2	12.2
	3:55	B		42.7	34.6	5.4	
		C		44.0	33.6	5.4	
3	4:00-	A	1644	48.3	34.0	5.8	13.1
	4:05	B		41.4	39.7	4.8	
		C		39.2	42.0	5.9	
4	4:30-	A	1368	45.3	30.2	6.6	7.9
	4:35	B		42.4	32.2	6.7	
		C		41.8	32.7	7.0	
5	4:40-	A *	1596	35.2	45.3	3.9	4.5
	4:45	B		19.8	80.5	3.5	
		C		30.0	53.3	4.5	
6	4:50-	A	1428	40.4	35.3	4.0	8.4
	4:55	B		32.6	43.8	7.2	
		C		37.7	37.9	4.6	
7	5:17-	A	1440	27.5	52.4	2.3	5.8
	5:22	B		21.7	66.5	5.4	
		C		23.3	61.9	4.1	
8	5:32-	A *	1404	17.2	81.6	4.5	8.5
	5:37	B		17.7	79.2	4.7	
		C		23.6	59.5	4.0	
9	5:45-	A *	1500	16.0	93.6	1.8	7.2
	5:50	B		19.9	75.4	3.7	
		C		26.4	56.8	3.1	
10	6:37-	A	1248	53.9	23.1	4.9	9.6
	6:42	B		49.9	25.0	5.1	
		C		51.0	24.5	5.0	
11	7:15-	A	1224	55.0	22.2	4.9	2.0
	7:20	B		50.8	24.1	4.4	
		C		51.6	23.7	4.1	
12	8:11-	A	912	55.6	16.4	5.2	6.6
	8:16	B		50.7	18.0	5.8	
		C		52.4	17.4	5.4	
13	8:26-	A	936	57.0	16.4	5.8	3.8
	8:31	B		52.8	17.7	5.6	
		C		54.0	17.3	5.4	

NOTE:

(1) Volume is 12 times 5-minute count for outside lane and is not corrected for truck percentage.

(2) Mean speed is calculated from sample size of 60 vehicles taken from 5-minute count.

(3) Density is calculated by dividing volume by mean speed.

(4) Truck percentage is for outside lane.

* "Stop-and-go" conditions.

Table 7. Tabulation of Shallowford Data Taken on August 30, 1967, by 20-pen Event Recorder

	Time PM	Area	Volume Q veh/hr	Mean Speed V mi/hr	Density K veh/mi	Standard Deviation S mi/hr	Truck Percentage T %
1	1:55-	J	828	53.3	15.5	8.6	30.5
	2:00	K		47.5	17.4	8.7	
		L		48.0	17.2	9.6	
2	2:16-	J	684	54.1	12.6	8.9	15.8
	2:21	K		48.2	14.2	8.6	
		L		50.4	13.6	10.2	
3	3:00-	J	912	56.4	16.2	6.9	22.4
	3:05	K		50.9	17.9	6.2	
		L		50.2	18.2	7.2	
4	3:20-	J	972	57.5	16.9	7.4	18.5
	3:25	K		51.4	18.9	6.8	
		L		52.7	18.4	9.1	
5	3:40	J	960	54.1	17.7	7.1	12.5
	3:45	K		51.3	18.7	6.9	
		L		53.1	18.1	4.5	
6	4:00	J	972	54.5	17.8	6.7	7.4
	4:05	K		50.9	19.1	6.6	
		L		52.5	18.5	6.2	
7	4:25-	J	924	55.5	16.6	7.9	11.7
	4:30	K		50.2	18.4	10.1	
		L		56.0	16.5	6.7	
8	4:35-	J	1344	52.6	15.6	2.8	11.6
	4:40	K		48.2	27.9	3.8	
		L		48.8	27.5	3.6	
9	4:50-	J	1056	51.7	20.4	8.1	11.4
	4:55	K		45.9	23.0	7.6	
		L		48.7	21.7	8.3	
10	5:00-	J	1488	31.7	46.9	4.2	4.0
	5:05	K		29.4	50.6	4.7	
		L		36.5	40.8	7.1	
11	5:12-	J *	1368	22.1	61.9	4.1	4.4
	5:17	K		19.7	69.4	4.0	
		L		37.0	37.0	4.7	
12	5:20-	J *	1308	18.2	72.9	5.9	5.5
	5:25	K		19.2	68.1	2.9	
		L		31.8	41.1	8.0	

NOTE:

(1) Volume is 12 times 5-minute count for outside lane and is not corrected for truck percentage.

(2) Mean speed is calculated from sample size of 60 vehicles taken from 5-minute count.

(3) Density is calculated by dividing volume by mean speed.

(4) Truck percentage is for outside lane.

* "Stop-and-go" conditions.

Table 8. Tabulation of Linear Regression Analysis of Speed versus Density Curves

Area	R	R^2	SEE	F	Equation
Peachtree Trial Test					
A	0.35	0.12	2.76	0.71	$V = 21.3 - 0.69\ K$
B	0.75	0.56	2.68	6.44	$V = 35.7 - 0.20\ K$
C	0.97	0.94	2.35	78.26	$V = 71.5 - 0.62\ K$
D	0.85	0.72	6.85	12.73	$V = 78.2 - 0.73\ K$
Peachtree Test					
A	0.97	0.94	3.77	161.38	$V = 65.3 - 0.58\ K$
B	0.99	0.97	2.40	362.09	$V = 62.3 - 0.57\ K$
C	0.99	0.98	1.78	462.05	$V = 66.9 - 0.71\ K$
Shallowford Test					
J	0.99	0.97	2.36	384.77	$V = 66.3 - 0.68\ K$
K	0.98	0.97	2.35	297.71	$V = 60.9 - 0.60\ K$
L	0.93	0.87	2.90	67.53	$V = 64.4 - 0.72\ K$

R = correlation coefficient.

R^2 = coefficient of determination.

SEE = standard error of estimate.

F = "F" value for F-Test.

Table 9. Comparison of Speeds Calculated by Aerial Photography and Time-Lapse Movies

	Photographs		Movie		
Vehicle	Distance Measured feet	Speed mi/hr	Distance Measured feet	Speed mi/hr	Difference d mi/hr
1	183	31.2	130	29.5	-1.7
2	180	30.7	100	28.4	-2.3
3	197	33.6	120	34.1	0.5
4	183	31.2	120	34.1	2.9
5	191	32.5	110	31.2	-1.3
6	188	32.0	110	31.2	-0.8
7	189	32.2	120	34.1	-1.0
8	192	32.7	120	34.1	1.4
9	102	17.4	100	18.9	1.5
10	114	19.4	110	20.8	1.4
11	108	18.4	110	17.9	-0.5
12	135	23.0	110	20.8	-2.2
13	180	30.7	120	34.1	3.4
14	162	27.6	100	28.4	0.8
15	168	28.6	110	31.2	2.6
16	111	21.0	120	19.5	-1.5
17	90	17.0	120	17.0	0
18	114	21.6	120	19.5	-2.1
19	138	26.1	100	22.7	-3.4
20	120	22.7	120	22.7	0
21	135	25.6	120	27.3	1.7
22	129	24.4	120	27.3	2.9
Average	150		114		0.10

Paired Observation Test:

Hypothesis-differences between speeds are zero.

$N = 22 \qquad \bar{d} = +0.10 \qquad S_d = 1.95$

$$t = \frac{\bar{d}\ N}{S_d} = \frac{(+0.10)\ (4.69)}{(1.95)} = +0.24 \text{ compared with}$$

$$t'_{(0.025),(21)} = \pm 2.080.$$

Therefore, there is insufficient evidence to reject the hypothesis that the speeds are the same.

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